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Fish migration in Mediterranean rivers: a case study of the fish pass assessment in Catalonia (NE Iberian Peninsula)

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Les migracions dels peixos als rius mediterranis: estudi de cas de l'avaluació dels dispositius de pas per a peixos de Catalunya (NE de la Península ibèrica)

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"***The ichthyomania (...) shows, as the most obvious symptom, a total incapacity to cross a bridge without looking into the water...***".

"***La ictiomania (...) mostra, com el símptoma més evident, una incapacitat total de creuar un pont sense fer un cop d'ull a l'aigua...***".

(Maurice Kottelat & Jörg Freyhof, 2007)

"***Eppur si mouve!***"

"***And yet it moves!***"

"***I no obstant això, es mou!***"

(Galileo Galilei, 1633)

Signat / Signed:

Frederic Casals i Martí	Marc Ordeix i Rigo
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Index

1. Resum / Resumen / Abstract

Resum

Pràcticament tots els peixos ibèrics d'aigües continentals migren clarament. La majoria són espècies potamòdromes però també n'hi ha de diàdromes. Els seus moviments migratoris són extensos en el temps, més a mesura que disminueix la latitud, i varien entre els anys. Les seves migracions són molt importants al període de fresa i, gairebé tot l'any, per a alimentació i refugi. Per això, si no és possible que els rius estiguin absolutament lliures d'obstacles transversals, com a mínim tots els dispositius de pas per a peixos haurien d'estar pràcticament sempre en funcionament.

Entre 2005 i 2010, es va dur a terme una avaluació preliminar de la connectivitat per als peixos dels rius de Catalunya mitjançant la inspecció directa de 95 dispositius de pas per a peixos. La majoria eren safareigs successius. L'eliminació de preses i rescloses i els dispositius de pas basats en solucions properes a la natura eren escassos. Només hi havia dispositius de pas a l'11% dels obstacles i molts (el 61%) eren inadequats o amb un manteniment incorrecte.

Es va fer una anàlisi *in situ* de l'eficàcia d'una selecció de 10 dispositius aparentment adequats. L'estimació de les taxes de pas de moltes espècies eren, amb algunes excepcions, massa baixes i, a la majoria dels casos, aquests dispositius només facilitaven les migracions dels peixos amb més capacitat de superar obstacles o els individus de major talla.

L'avaluació complementària *in situ* d'una rampa per a peixos considerada eficaç a priori (índex ICF de 95) va mostrar que permetia el pas de tots els ciprínids autòctons. El període de fresa va ser el principal impulsor de la migració riu amunt, que també es va veure influïda per la disminució de cabal just després de puntes de cabal, un mínim de temperatura de l'aigua i les fases lunars menys lluminoses.

Paraules clau: Migració de peixos, peixos continentals, Catalunya, Península ibèrica, rius mediterranis, període de fresa, connectivitat fluvial, rescloses, estacions d'aforament, dispositius de pas, rampes per a peixos, avaluació, índex ICF.

Resumen

Prácticamente todos los peces ibéricos de aguas continentales migran claramente. La gran mayoría son especies potamódromas pero también hay de diádromas. Sus movimientos migratorios son extensos en el tiempo, más a medida que disminuye la latitud, y varían entre los años. Sus migraciones son muy importantes en el periodo de freza y, casi todo el año, para alimentación y refugio. Así, si no es posible que los ríos estén absolutamente libres de obstáculos transversales, como mínimo todos los dispositivos de paso para peces deberían estar practicamente siempre en funcionamiento.

Entre 2005 y 2010, se llevó a cabo una evaluación preliminar de la conectividad para los peces de los ríos de Cataluña mediante la inspección directa de 95 dispositivos de paso para peces. La mayoría eran estanques sucesivos. La eliminación de presas y azudes y los dispositivos de paso basados en soluciones próximas a la naturaleza eran muy escasos. Sólo había dispositivos de paso en el 11 % de los obstáculos y muchos de ellos (el 61%) eran inadecuados o con un mantenimiento incorrecto.

Se efectuó un análisis *in situ* de la eficacia de una selección de 10 dispositivos aparentemente adecuados. La estimación de las tasas de franqueo de muchas especies eran, con algunas excepciones, demasiado bajas y, en la mayoría de los casos, estos dispositivos sólo facilitaban las migraciones de los peces con mayor capacidad de superar obstáculos o los individuos de mayor talla.

La evaluación complementaria *in situ* de una rampa para peces considerada eficaz a priori (índice ICF de 95) mostró que permitía el paso de todos los ciprínidos autóctonos. El periodo de freza fue el principal impulsor de la migración río arriba, que también se vio influida por la disminución de caudal justo después de puntas de caudal, un mínimo de temperatura del agua y las fases lunares menos luminosas.

Palabras clave: Migración de peces, peces continentales, Catalunya, Península ibérica, ríos mediterráneos, período de freza, conectividad fluvial, azudes, estaciones de aforo, dispositivos de paso, rampas para peces, evaluación, índice ICF.

Abstract

Almost all Iberian freshwater fish clearly migrate. The great majority are potamodromous but there are also diadromous species. Their migratory movements are extensive in time, greater at lower latitudes, and vary over different years. Migrations take place particularly in the spawning period and throughout the year for feeding and refuge. Thus, if rivers were not absolutely free of transverse obstacles, at least, all fish passes would almost always be in operation.

Between 2005 and 2010, a preliminary evaluation of river connectivity for fish in Catalonia was conducted through direct inspection of 95 devices. Most of them were pool fish passes. Dam and weir removal and close-to-nature fish passes were uncommon. Fish passes were only present at 11% of river obstacles and many of these (61%) were inappropriate or poorly maintained.

An *in situ* analysis of the effectiveness of 10 of these selected fish passes was carried out. The crossing rates estimated for many species, were, with few exceptions, too low and, in most cases, only fish with a high capacity for overcoming obstacles or the largest individuals succeeded in migrating.

A complementary *in situ* assessment of a fish ramp considered effective a priori (ICF index of 95) showed that it allowed passage of all native cyprinids. The spawning period was a primary driver of upstream fish migration, which was also influenced by the decrease in river flow just after a peak flow, a minimum water temperature and less bright lunar phases.

Key words: Fish migration, freshwater fish, Catalonia, Iberian Peninsula, Mediterranean rivers, spawning period, river connectivity, weirs, hydropower, gauging stations, fish passes, fish ramps, assessment, ICF index.

2. General introduction

2.1. Ecological connectivity in freshwater systems

Human activity has altered rivers, lakes and wetlands and their biodiversity. As in other European, Mediterranean and Iberian regions, freshwater fish in Catalonia have been affected, to varying degrees, by a combination of problems: overexploitation of water, i.e. direct and diffuse pollution, and excessive intakes; overfishing, by professionals in estuaries and on the coast, and by anglers across the entire region, especially at headwaters of rivers and streams; competition from a growing number of invasive species; and the existence of obstacles to migration, particularly dams and weirs, thereby causing poor ecological connectivity for fish.

The widely used definition of ecological continuity (or connectivity) is *"such habitat has been available in patches for a long time within the limits of a landscape, in which the juxtaposition of habitat patches is important for dispersal and metapopulation dynamics of species. The spatial scale of 'landscape continuity' is usually undefined and may be different for different organisms"* (Nordén & Appelqvist, 2001).

Ecological connectivity can be understood as the functional "*exchange pathway of matter, energy and organisms*" (Ward & Stanford, 1995; EC, 2000). An obstacle is considered very permeable, with very good connectivity, if it includes an effective solution for fish passage. This means that it should allow at least 95% of all species and individuals to travel through it, both upstream and downstream, and operate correctly in 95% of flows known at each site (Mallen-Cooper, 1993; Thorncraft & Harris, 2000). An obstacle or a fish pass is considered impermeable, with poor connectivity, if it does not allow any species to pass through it or only a few individuals in exceptional hydrological conditions. Obviously, there is a wide range of intermediate situations.

Currently, most fish can no longer migrate to complete their life cycle in most of the world because their natural habitats are modified. River obstacles have direct effects on population biology, such as local extinctions due to a lack of dispersion and recolonisation, genetic isolation, lack of access to spawning areas, feeding areas, refuges from predators and shelter areas, or due to harmful environmental conditions, i.e. pollution, large-scale flooding, droughts or other human disturbances and natural disasters (Lucas & Baras, 2001).

The most important factor for several Mediterranean freshwater fish species is the longitudinal dimension. Poor longitudinal connectivity in inland waters affecting both upstream and downstream migrations is associated with many instream structures, from large dams and weirs, to channels for irrigation or hydroelectric plants, turbines and pumping stations, gauging stations, and other factors, such as hydrological and water quality constraints.

The existence of transverse obstacles in rivers, preventing water, sediments and fauna from flowing, has significant ecological consequences because the hydromorphological and biological conditions of the ecosystem are directly or indirectly affected (Cowx & Welcomme, 1998). Water abstraction may change a perennial stream to an intermittent one, increasing the duration and magnitude of droughts and limiting the stream's ability to support aquatic biota. Total or partial retention of water and sediments leads to loss or alteration of water habitats upstream and downstream of the obstacle (Larinier, 2001) and affects the distribution, abundance and survival of species present.

These structures profoundly disturb the hydromorphology of rivers (slowing of flow velocities, increased depths, reduction or halt of coarse sediment transport, etc.) and provoke major physical and chemical modifications in water. In addition to limiting movement of living communities, obstacles to river flow also have an impact on ecological continuity by altering the quality and reducing the diversity of the habitats available to the various aquatic species (Baudoin et al., 2014).

Major obstacles that act as complete barriers to upstream (and frequently also downstream) fish passage, such as large dams and weirs, isolate and modify previously contiguous fish communities, which results in drastic changes in the faunal community structure of river ecosystems (Thorncraft & Harris, 2000). These obstacles represent barriers to the migration of many aquatic and semi-aquatic species, and thus they have direct effects on population biology, such as causing local extinctions due to a lack of dispersion and recolonisation, genetic isolation, impediments to reproduction, and non-accessibility to feeding resources and shelter areas (Lucas & Baras, 2001).

A barrier may represent a complete obstacle to migration if it cannot be overcome by any member of a given species under any circumstances. It may also be a partial obstacle in that it cannot be overcome by some fish and it may be a temporary obstacle in that it cannot be overcome during certain periods of the year. The negative impact of temporary obstacles should not be underestimated because they can delay fish during their migration and may oblige them to wait in unfavourable areas and/or may result in injuries or mortalities, including increased risk of disease and predation, following repeated, unsuccessful attempts to pass (Baudoin et al., 2014).

In Catalonia, migration routes of native fish, some of which are Iberian endemisms, were damaged in past centuries. Large migratory species, such as the European eel (*Anguilla anguilla*), are not present upstream of dams. Twaite shad (*Alosa fallax*), European sturgeon (*Acipenser sturio*), which is locally extinct, and sea lamprey (*Petromizon marinus*) populations are similarly affected (Doadrio, 2001; Sostoa et al., 2003) while other non-diadromous fish have also had their migration routes negatively affected and are consequently now endangered.

Further to altering the habitat of diverse, valuable, native Mediterranean species, most of them associated with running water, transforming rivers into a series of ponds (often with quantities of fine sediments) has especially benefited invasive fish species (Vinyoles et al., 2007) such as common carp (*Cyprinus carpio*), black bullhead (*Ictalurus melas*), roach (*Rutilus rutilus*) and common bleak (*Alburnus alburnus*).

Rivers with poor connectivity are considered one of the main causes of many freshwater fish species decline in the Iberian Peninsula (Doadrio, 2001; Santo, 2005), Europe (Bruslé & Quignard, 2001; Larinier, 2002a; Kottelat & Freyhof, 2007) and worldwide (Gough et al., 2012). Although some species can complete their life cycle in highly fragmented rivers, when they have free space, they carry out much longer migrations (Geeraerts et al., 2007).

Fish species that perform significant migrations during their life cycle, particularly anadromous and catadromous, locally disappear when obstacles are established. For example, it has been estimated that 30 major reservoirs in the main course of the River Ebre (NE Iberian Peninsula) are the main cause of a decline of 65% in sea lamprey (*P. marinus*), 100% in European sturgeon (*A. sturio*), 60% in shads (*Alosa* spp.), 85% in European eel (*A. anguilla*) and 60% in mullets (mugilids) that potentially shelters (Nicola et al., 1996).

Conservation of fish diversity is one of the most critical issues for preserving overall European biodiversity (Zitek et al., 2008). This issue is gaining prominence not only because of the decline in some commercial fish species, such as European eel (*A. anguilla*), but also because of the increasing environmental awareness among people of the importance of improving the ecological quality of ecosystems in general and the mobility of aquatic fauna in particular.

Native species of Mediterranean rivers have a wide range of tolerance to environmental variations and they are habitat and feeding generalists, well adapted to survive in changing environments (Ferreira et al., 2007). Nonetheless, there is a poor knowledge of their ecological requirements (Smith & Darwall, 2006).

Restoration of fish migration should pay proper attention to dam and weir removal, which is the most environmentally positive solution in the medium and long term (Gough et al., 2012); a total restoration of longitudinal river connectivity is only possible by demolishing obstacles (Zitek et al., 2008). If the obstacle has cultural value or its current use (hydropower, irrigation, etc.) do not allow removal, close-to-nature fish passes, such as lateral channels and fish ramps, which provide optimum conditions for a wider range of species, individuals and flows (Marmulla & Welcomme, 2002), are a good option. Rehabilitation measures should ensure the re-establishment of a good ecological status of rivers according to the European Water Framework Directive (WFD; 2000/60/EC), and the conservation of endangered freshwater species included in the Habitats Directive (92/43/CEE). They are also extremely important for the European Plan for Eel Recovery (Regulation 1100/2007).

WFD requires achievement of a good ecological status for all riverine water bodies, which can only be accomplished when fish communities are close to natural conditions and, thus, when longitudinal river connectivity improves. Water pollution and eutrophication processes have already decreased in Catalan rivers (ACA, 2009). In addition, the previously implemented Spanish Inland Fisheries Act (1942), which already made it obligatory to build fish passes, was updated in Catalonia (*Llei 22/2009, del 23 de desembre, d'ordenació sostenible de la pesca en aigües continentals*), supporting the construction of new fishways to improve fish community integrity. To achieve these environmental objectives, it is important to use assessment tools that can be applied to extensive geographical areas while producing a reliable estimation of fish pass effectiveness to improve the design, construction, management and restoration solutions for fish migration.

This rehabilitation should include effective fish passes and also connection with well-preserved source areas and habitat recovery (Zitek et al., 2008). Thus, implementation of environmental flow regimes is urgently needed because without it other measures could be useless.

River connectivity for fish is assessed to measure the difficulty of reaching a good ecological status (in line with the FWD) according to the degree of connection between different parts of the river or between sections of the river and the sea. This factor is usually analysed from the perspective of connectivity for wildlife, specifically in fish populations, so many techniques are designed to assess the potential for dispersion and recolonisation.

However, the capacity of native fauna to use fish passes and their natural patterns of movement, especially in Mediterranean rivers, is still poorly understood (Marmulla & Welcomme, 2002). Fish pass assessments could also provide important knowledge regarding fish movement patterns (Lucas & Baras, 2001; Roni, 2005).

Figure 1. Possible solutions to improve longitudinal connectivity at a river obstacle (a weir, top): restoration (weir removal, middle) and rehabilitation (close-to-nature fish pass, a fish ramp; bottom). Pictures: Toni Llobet (top and bottom) from Ordeix et al. (2007), and Acíclic (middle) from Ordeix et al. (2014).

2.2. Solutions to improve freshwater fish migration

Recovery of river connectivity in order to restore components affected by an obstacle (water, chemicals, sediments and biota) and their natural dynamics can be achieved through demolition of the obstacle (Marmulla & Welcomme, 2002; Armstrong et al., 2004; Gough et al., 2012). If transverse infrastructures are no longer in use or if authorisation for their use has lapsed, it may be possible to remove them, partially or totally.

However, restoration of ecological connectivity is not habitually possible if the obstacle has some socioeconomically important use, historical or cultural heritage value, or is used for hydropower generation or water intake to supply or irrigate, among other uses. In such cases, usually in areas with significant human population, improving river connectivity may consist in the installation of some fish pass in the obstacles to help migrating fauna, both upstream and downstream.

The main biological goal of dam removal and fish passes, rather than to enable the entire population downstream of the obstacle to pass upstream, is to avoid isolation of fish populations between different reaches or areas (Porcher & Travade, 2002).

The installation of a fish pass does not guarantee absolutely effective re-establishment of ecological connectivity because its degree of functionality depends on construction criteria, its maintenance and management, and its suitability for the native fauna and the type of river stretch.

According to international references (Larinier *et al*., 1994; Thorncraft & Harris, 2000; Larinier, 2001; Marmulla & Welcomme, 2002; Armstrong *et al*., 2010; Gough *et al*., 2012; Baudoin et al. 2014), solutions for the recovery (restoration; Fig. 1 (middle)) or improvement (rehabilitation; Fig. 1 (bottom)) of longitudinal river connectivity may be classified into two major types:

a) **Restoration**: implies a total return to an original pristine state by removing obstacles partially or completely; water quality and habitat improvement as well. Restoration is considered the most appropriate option from the environmental point of view because it allows full recovery of river continuity, because it also involves, for example, the release of sediment transport.

b) **Rehabilitation**: involves taking actions to improve connectivity, but without overall full habitat restoration, including:

b1. <u>Fish passes</u>, ranging from:

- *Close-to-nature solutions*, such as fish ramps, bottom or rock ramps and by-pass channels or streams.
- *Broad-spectrum technical solutions*, such as pool fish passes (with or without drops), slot passes or vertical slot fishways, deflectors, denil or baffle fish passes.
- *Mechanical or specific technical solutions*, such as eel ladders, fish lifts, fish locks, siphons and fish pumps.

b2. <u>Systems for fish protection</u>, especially associated with downstream fish migration, such as mechanical, electrical or light barriers and spillways against the entrainment of fish into channels or turbines.

b3. <u>Adjusted management</u>: it entails a set of actions performed at particular times to improve fish migration, such as the implementation of environmental flow regimes, operation of regulation or protection sluices, and fish-friendly ship locks and turbines management.

Dam and weir removal is increasingly used in recent years. For now, most demolitions have been carried out in the United States of America, where in the last 75 years hundreds have been eliminated. In the European Union, many dams have also been demolished, especially in France, specifically in the Loire river basin (where wide publicity was given to the case of Saint-Étienne du Vigan sur l'Allier, removed in 1998) and also in Spain, especially in Basque Country, Navarra and Duero river basin. Only a few cases of small weir removal have been carried out in Catalonia (NE Iberian Peninsula) over the last few decades: along the Sorreigs stream (Ter river basin) and along the Ripoll river (Besòs river basin).

However, if the uses or heritage value do not allow obstacle removal, several systems of river connectivity rehabilitation may ensure the reestablishment of a good ecological status, following the requirements of the Water Framework Directive. Fish passes are the most common option.

Fish passes should be prioritised in terms of effectiveness for all groups of potentially present native fish fauna in each river section. This should include groups of species with different swimming or jumping capabilities, as well as those that are not associated with any commercial or sporting interest or special conservation value. Fish pass effectiveness is highly dependent on the ease of maintenance and management, which should be considered at an early stage in the design process, as indicated by numerous references (Jungwirth *et al.*, 1998; Marmulla & Welcomme, 2002; Garcia *et al.*, 2005; Santo, 2005; Armstrong *et al.*, 2010; Gough et al., 2012; Baudoin et al. 2014). Thus, the installation of a fish pass alone is not a guarantee of longitudinal connectivity recovery for fish. Basic considerations on fish passes have to be made:

a) **Upstream migration**: migrating fish must find the fish pass entry easily and without delay. A critical point here is the location of the fish pass entrance and the attraction flow for fish in relation to the overall flow at the base of the obstacle; attraction flow should be at least 10% of the average annual flow of the section where it is located (Larinier et al., 2002b). Turbulence within the fish pass must also be restricted to an appropriate level associated with the tolerance of the species that could use it (i. e. shads do not accept turbulence; Larinier et al., 2002d). The fish pass should be placed at one of the river sides, parallel to the dominant direction of flow, and its bottom should preferably be rough.
b) **Downstream migration**: when fish migrate downstream, they must be guided away from potentially damaging components of the obstacles (e.g. turbines, pumps, racks) to a spillway or the fishway exit. Behavioural and/or physical barriers (e.g. screens, lights, sounds) may be appropriate to guide fish to an alternative route for downstream migration. It is also important to avoid big jumps, which would be fatal to fish when water velocity exceeds 15-16 m/s, e.g. when the free fall is equal to or greater than 13 m if the fish is over 0.60 m, or 30-40 m if the fish is 0.15-0.16 m (Larinier et al., 2002b).

c) **Maintenance**: the fish pass should work effectively without frequent maintenance. A factor of poor performance of these facilities frequently revealed is clogging up or obstruction of the fish pass, resulting from inadequate protection against debris, too exposed position, or quite simply inadequate maintenance on the operator (necessary, for example, with the pool fish passes). Obstruction caused by floating debris can result in insufficient water flow in the fish pass (blockage of notches or slots, clogging of the screens of the auxiliary water system, etc.) and impede fish passage (Larinier, 2002e).

Assessment of the effectiveness of fish passes can be accomplished by gathering information on obstacle and fishway characteristics so that the degree of impediment for fish passage can be evaluated. However, fish pass effectiveness can also be estimated from fish species crossing rates, which are calculated using a wide array of methods ranging from the installation of fish traps at the water intake upstream of the fish pass, to the comparison of fish populations on both sides of the obstacle, group mark-recapture methods (upstream and downstream fish populations), individual mark-recapture methods (e.g. with PIT tags), automatic fish counters, visual counts, telemetry or hydroacoustic approaches (Lucas & Baras, 2001; Travade & Larinier, 2002; Marmulla & Welcomme, 2002; Roni, 2005; Santos *et al.*, 2006; Baudoin et al. 2014).

Longitudinal river connectivity has been poorly studied in the Iberian Peninsula. In Catalonia, only some of the river obstacles present have been assessed (Elvira *et al.*, 1998a; Elvira *et al.*, 1998b; Catalán *et al.*, 1997; Ordeix *et al.*, 2011; Aparicio et al., 2012).

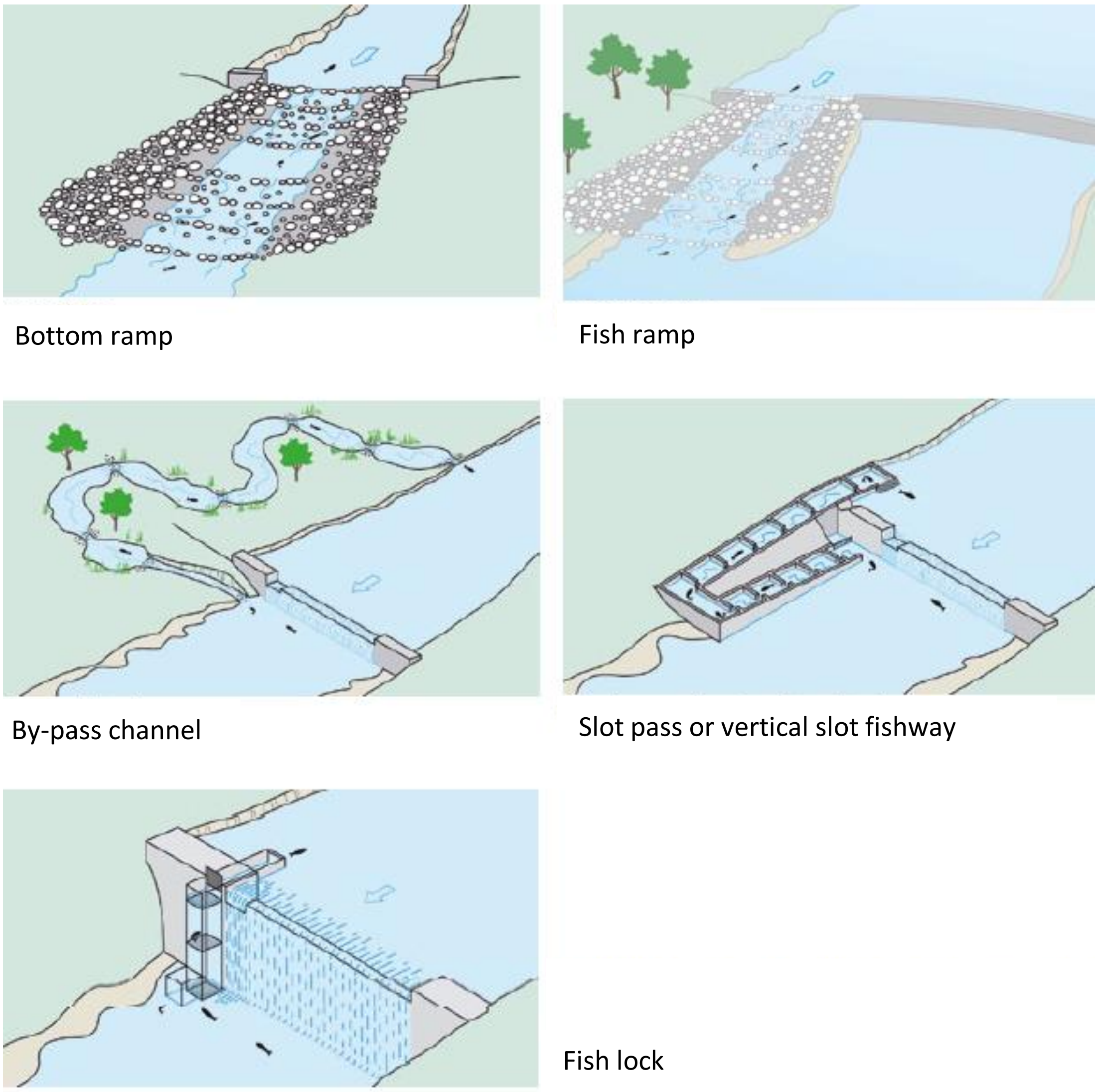

Figure 2. Possible rehabilitation solutions, fish passes, to improve fish migration: close-to-nature fish passes (bottom ramp, fish ramp and by-pass channel), broad-spectrum technical solutions (slot pass or vertical slot fishway) and a mechanical solution (fish lock). Pictures: redesigned by Acíclic from Ordeix et al. (2014), based on Thorncraft & Harris (2000).

3. General objectives

The general objectives of this study are:

1. Improve knowledge of fish migration in Catalonia, the Iberian Peninsula and Mediterranean freshwaters.

2. Review a significant portion of the available information (publications and databases) of freshwater fish biology and ecology and fish pass assessments in spawning and migrating periods, and other possible associated causes of migrations, for the whole Iberian Peninsula.

3. Count, characterise and assess the fish passes present in Catalan rivers until 2010, using several assessment techniques: quick assessment techniques basically associated to the ICF index calculation, for the estimation of fish pass effectiveness of all of them (95), and methods that estimate fish crossing rates in the fish passes and comparing fish populations upstream and downstream of a selection of fish passes (10 + 1).

4. Describe possible constraints and solutions for several fish species, age groups and sexes for use of different fish pass types.

5. Test and propose methods to improve and assess construction and management of fish passes and fish migration in Catalonia, the Iberian Peninsula and Mediterranean freshwaters.

4. Methods

We collected and compared almost all available information (publications and databases) relating to periods of migratory activity for native freshwater fish species of the Iberian Peninsula (SW Europe), spawning (reproductive) periods and other possible associated causes of migrations.

Furthermore, we carried out a census of fish passes in Catalonia (NE Iberian Peninsula) and a preliminary test of the effectiveness of all of fish passes identified (95 until 2010). Fish pass monitoring knowledge is great around the world (Lucas & Baras, 2001; Travade & Larinier, 2002; Marmulla & Welcomme, 2002; Roni, 2005; Baudouin et al., 2014). A European Standard for fish pass performance could arrive soon (Washburn et al., 2015), but is still pending.

Different types of fish passes of several river basins at 10 + 1 sites were also evaluated, including different environmental conditions and typologies. Methodologies used depended on the river flow and type of fish pass and the kind of location, among others, and also were subject to technical and financial resources available.

Close-to-nature devices assessment in Catalan rivers is still mostly pending. Specifically, a fish ramp (at the gauging station of the River Fluvià at Olot), which follows international guidelines for fish passes and, especially, for fish ramps (Gebler, 1998; Larinier, 2002d; Marmulla & Welcomme, 2002), was assessed during the spawning period, out of it and under different environmental conditions, to improve knowledge on main causes and capabilities for migration of several Mediterranean freshwater fish.

Evaluation of effectiveness of a selection of fish passes has been conducted by directly or indirectly estimating the permeability rate of fish species using different methodologies (Lucas & Baras, 2001; Travade & Larinier, 2002; Marmulla & Welcomme, 2002; Roni, 2005; Santo, 2005; Baudouin et al., 2014). These methods are relatively expensive and require mid- or long-term monitoring. They require fish population surveys and, in some cases, use of marking and recapture methods.

Additionally, they depend on previous knowledge regarding species phenology because fish movements in rivers are usually concentrated in particular seasons and the use of a specific method can vary due to many factors (Lucas & Baras, 2001).

In brief, we analysed longitudinal connectivity throughout fish passes by using an index of river connectivity (95), and *in situ* (indirect and direct) fish pass assessment effectiveness estimation techniques only for some of them (10 + 1), following useful previous criteria for Iberian rivers (Santos et al., 2006; Ordeix et al., 2011; Ordeix et al., 2014):

1. **General data collection**: using rapid assessment techniques, including the calculation of the ICF index (River Connectivity Index; Solà *et al*., 2011), specially designed for Catalan rivers (adaptable to other Mediterranean and European rivers), to assess the theoretical degree of impediment for all counted fish passes in Catalonia until 2010.
2. ***In situ* estimation techniques**:
    a. **Indirect estimation techniques**: using trapping fishing systems and/or electric fishing systems (CEN standard norm *UNE-EN 14011:2003*) to compare fish population structure above and below the fish pass (Travade & Larinier, 2002; Roni, 2005) everywhere (10 + 1 sites); mark-recapture methods and individual mark-recapture methods, using passive integrated transponders (PIT tags) at two sites.
    b. **Direct estimation techniques**: installing fish traps at the water intake of each assessed fish pass (10 + 1) to compare fish using the fish pass with the potentially migrating downstream fish population, obtained by using electrofishing systems (depletion sampling; Zippin, 1958), mainly using fish crossing rates and/or deviations of size frequencies (Lucas & Baras, 2001; Roni, 2005). In one place, despite being limited by water turbidity and the presence of a large number of migrating fish, visual counts (Travade & Larinier, 2002; Marmulla & Welcomme, 2002) were made as well.

4.1. General data collection

Preliminary assessment of fish longitudinal connectivity in Catalan rivers was based on field visits carried out between 2005 and 2010 (partially published in Ordeix et al., 2011). This consisted of an inspection and collection of information to complete a database of obstacles to freshwater fish migration and their associated fishways to be used by the Catalan Water Agency (ACA) managers.

River habitat and riparian vegetation indexes, IHF (Pardo *et al.*, 2002), RBPs (only in some sites; Plafkin *et al.*, 1989; Barbour *et al.*, 2002) and QBR (Munné *et al*, 1998), were preliminarily obtained. Physicochemical parameters (water temperature, electric conductivity, pH and dissolved oxygen) were calculated by using a multiparametric portable YSI Professional probe. Daily average river flow was reported by the Catalan Water Agency (ACA). Several physical variables were measured at each hydraulic device, including velocities by using a Global Water FP101 flow meter, operating levels, and water depths and waterfall heights at each obstacle and several sections of each fish pass.

To assess the theoretical degree of impediment for fish passage, the ICF index (River Connectivity Index; Solà *et al.*, 2011) was also calculated everywhere.

ICF index

A preliminary step in prioritising the restoration of longitudinal river connectivity is the evaluation of the degree of impact of structures that might generate discontinuity and the effectiveness of existing fish passes. Furthermore, this is also a requirement of the WFD, as it specifies that river connectivity is one of the hydromorphological items that must be evaluated within an ecological status assessment. However, obtaining estimations of fish permeability rates through specifically designed surveys for each individual obstacle found in a water agency domain is prohibitive in terms of cost and effort, especially if this must be repeated periodically. Moreover, it is also important to take into account that fish species can encounter many obstacles during migration, and all of them must be evaluated. In this context, the development of a simple indicator allowing estimation of obstacle permeability (with or without fish passes) without requiring biological samples was needed.

Although different hydromorphological quality indexes exist, such as SERCON in Scotland (Boon et al., 1997 & 1998), RHS in the United Kingdom (Raven et al., 1998), together with its subsequent adjustments in other countries, SEQ-Physique in France (Agences de l'Eau, 2002), LRS in Germany (Fleischhacker & Hern, 2002), DSHI in Denmark (Pedersen & Baattrup-Pedersen, 2003), Caravaggio in Italy (Buffagni et al., 2005), and CEN rule (CEN, 2010), longitudinal river connectivity has always been poorly assessed. Recently, the ICE protocol appeared, developed in France and Belgium (Baudoin et al., 2014), and the Spanish Ministry of Agriculture, Food and the Environment published a protocol on river connectivity monitoring (MAGRAMA, 2015).

A first version of the river connectivity index ICF (from the Catalan "Índex de Connectivitat Fluvial") was designed as part of a procedure to assess the hydromorphological quality of Catalan rivers (HIDRI protocol-ACA, 2006). Application of this index by several consultancies and research centres (Ferrer et al., 2009; Rocaspana et al., 2009; Ordeix et al., 2011) revealed the existence of deficiencies that yielded a final result that did not coincide with real longitudinal connectivity independently evaluated. The ICF index was finally improved and tested by members of the Catalan Water Agency (ACA) in collaboration with the Center for the Study of Mediterranean Rivers – Ter River Museum (Solà et al., 2011).

The last version of the ICF index assesses the theoretical degree of impediment for fish passage, based on comparison between the physical characteristics of the obstacle and the fish pass (if any) and the swimming and/or jumping skills of the potential fish fauna present in the evaluated river section (Table 1 and Fig. 3). The ICF is divided into three blocks that encompass assessment of the obstacle (Fig. 4) and the fish pass (Fig. 5), together with the estimation of certain modulators. Finally, the ICF classifies connectivity into five levels from very good to bad, depending on the degree of permeability for different fish groups, discriminating among infrastructures based on the chance that they can be crossed by all species, by only some species, or by no species (Table 2).

It enables the evaluation of river connectivity across a wide area, such as Catalonia, including a large number of obstacles to be targeted and medium- to long-term monitoring. Additionally, the ICF index is complementary to *in situ* estimations of fish crossing rates, as they both discriminate between infrastructures based on the chance that they can be crossed by all species, by only some species, or by no species.

The ICF index (Solà *et al*., 2011) was tested for 101 transverse obstacles in rivers in Catalonia, both with and without fish passes, with results in the five expected quality levels (from very good to bad), and it is considered coherent with the real permeability of the obstacles. Its ease of application compared to *in situ* measurements of fish movements and the detailed information recorded by the index make it a very useful tool for the diagnosis of the longitudinal connectivity of rivers and for guiding measures for hydromorphological quality improvement.

The ICF index can easily be adapted to other regions: it has already been used for almost all the river basins of Portugal (J. M. Santos, com. pers.) and several river basins in Spain, such as the Segura river basin and the Júcar river basin. As with other Iberian river connectivity indexes (Índice de Franqueabilidad, IF; Seisdedos et al., 2008), its interest is also as a tool for prioritising river connectivity improvement measures, in expert analyses, or used in combination with other indexes (Índice de Prioridad de Actuación (IPA); Seisdedos et al., 2008).

Group	Definition	Species present
Group 1 (G1)-Littorals and similar	Migratory species (anadromous or amphidromous) with short or long distance movements, with a moderate or low capacity to overcome obstacles	
Group 1a (G1a)	Large species, with a moderate capacity to overcome obstacles	*Alosa alosa* *Alosa fallax* *Liza ramada* *Chelon labrosus* Mugil cephalus
Group 1b (G1b)	Small or benthic species, with a low capacity to overcome obstacles	*Atherina boyeri* *Platichthys flesus* *Petromyzon marinus*
Group 2 (G2)-eels and similar	Migratory species (catadromous), with long distance movements and high capacity to overcome obstacles but not able to jump	*Anguilla anguilla*
Group 3 (G3)-cyprinidae and similar	Intra-river migratory species (potamodromous) with a moderate or low capacity to overcome obstacles	
Group 3a (G3a)	Large species, with a moderate capacity to overcome obstacles	*Barbus meridionalis* *Barbus haasi* *Luciobarbus graellsii* *Squalius laietanus* *Squalius pyrenaicus* *Parachondrostoma miegii* *Cottus hispaniolensis*
Group 3b (G3b)	Small species, with little capacity to overcome obstacles	*Phoxinus bigerri* *Phoxinus phoxinus* *Barbatula quinardi* Salaria fluviatilis *Cobitis* sp. *Achondrostoma arcasii* *Gasterosteus aculeatus*
Group 4 (G4)-trout and similar	Intra-river migratory species (potamodromous) with a high capacity to overcome obstacles, by swimming and/or jumping	*Salmo trutta*

Table 1. Grouping of the most characteristic fish species in Catalan continental waters that was used in the design of the ICF according to their ability to overcome obstacles and their presence in different types of river sections. From: Solà et al. (2011).

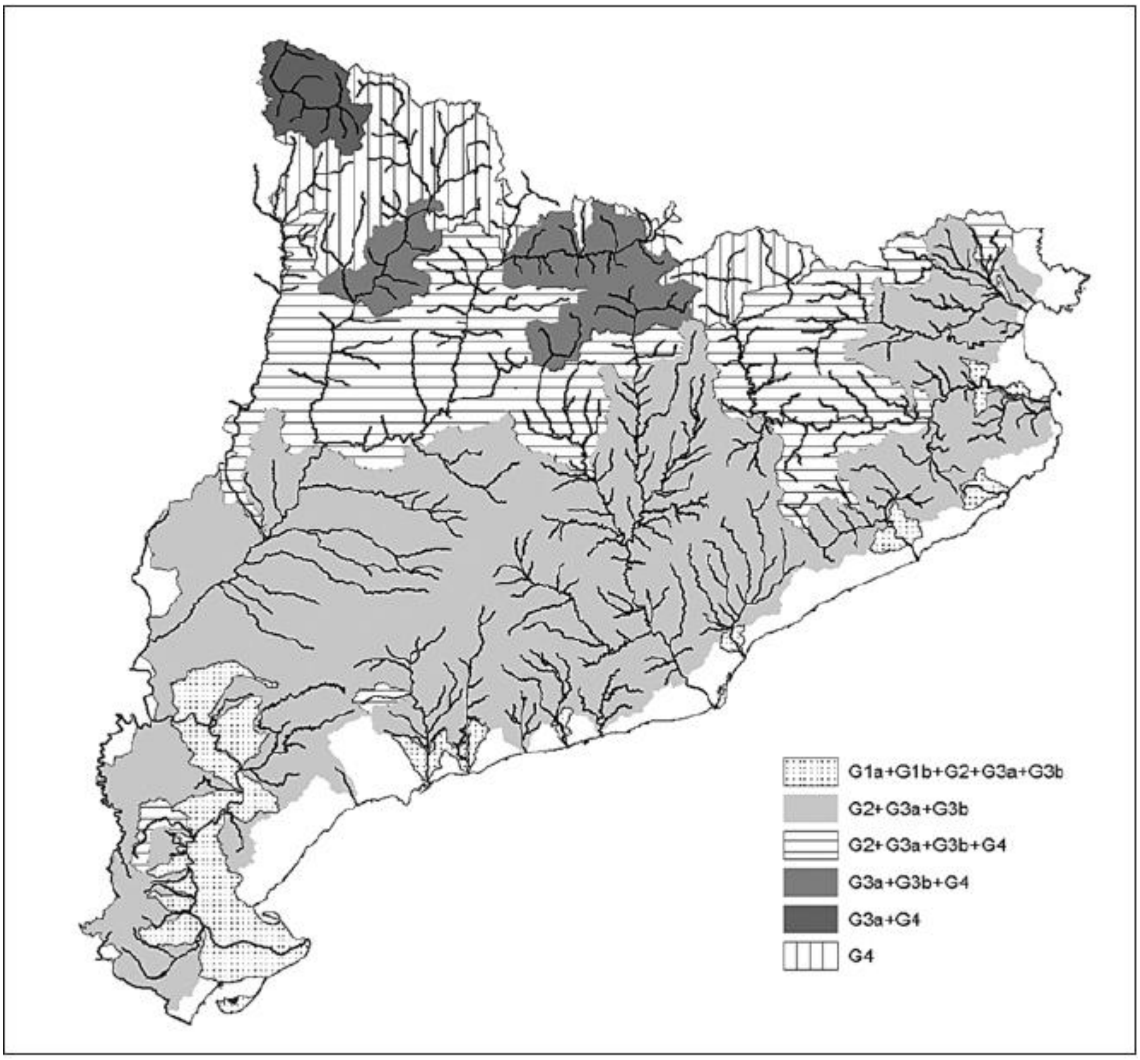

Figure 3. Potential distribution of native continental species in Catalonia (NE Iberian Peninsula) grouped according to their capacity to overcome obstacles and their presence in different types of river sections (following Fig. 2). From: Solà et al. (2011).

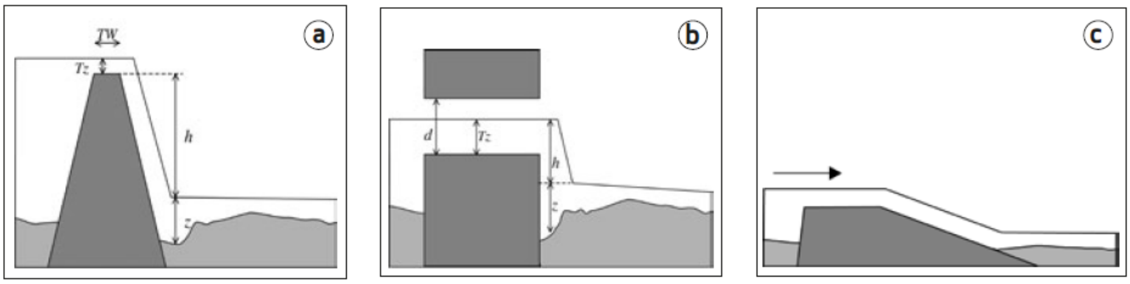

Figure 4. Illustrations and measurements of transverse river obstacle types to which the ICF can be applied (*d*, *h*, *TW*, *Tz* and *z*). a) Structures where water passes over the obstacle creating a small waterfall (weir type); b) structures where water passes through one or several holes, with or without a small waterfall (culvert type); c) structures with a very low slope, where water passes over and does not generate any small waterfall. From: Solà et al. (2011).

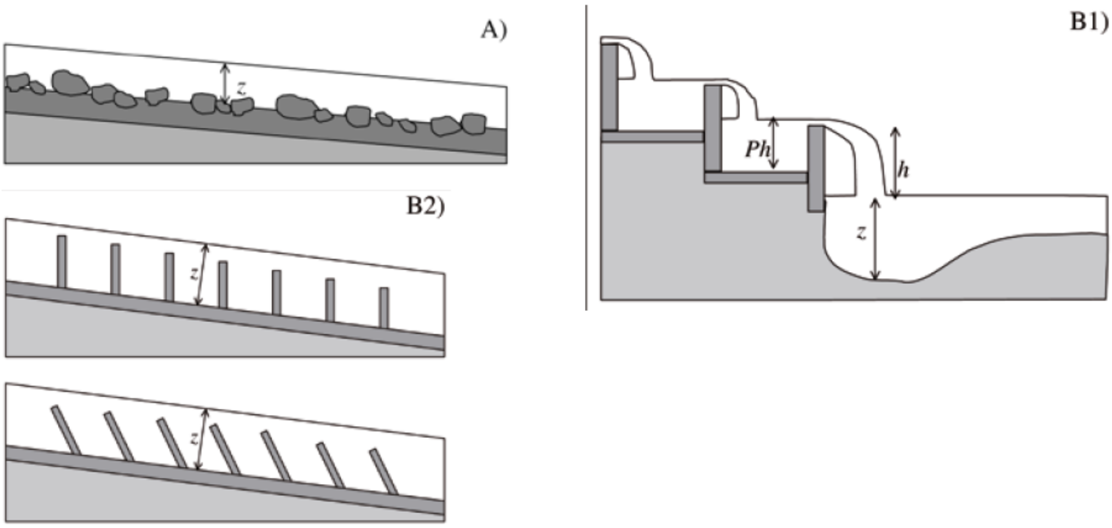

Figure 5. Illustrations and measurements of the different fish passes to which the ICF can be applied (*h*, *Ph* and *z*). A) Fish passes close to natural conditions, such as fish ramps, lateral rivers or canals, or similar devices; B1) broad spectrum technical solutions such as pool fish passes or similar structures; B2) broad-spectrum technical solutions such as baffle type fish passes (deflectors, retarders) or similar structures. From: Solà et al. (2011).

Table 2. Quality classes and score range of the ICF index and general interpretation. Adapted from Solà et al. (2011).

	Range	Quality	Interpretation
I	≥ 95	Very Good	All the potentially present groups of fish can pass in nearly any hydrological situation. Absence of obstacles for fishes or existence of a partial or total demolition of an obstacle for fishes.
II	75-94	Good	The majority of the potentially present fish groups can pass in nearly any hydrological situation. Presence of a small obstacle or with a good fish pass for fishes.
III	50-74	Moderate	The majority or some of the potentially present fish groups can pass, in any or in some hydrological conditions. Presence of a relatively permeable obstacle for fishes with too specific or little functional fish pass for fishes.
IV	25-49	Poor	Only one or few species of the potentially present fish groups can pass, and in determined hydrological situations. Presence of an obstacle with very specific or very little functional fish pass.
V	< 25	Bad	No species of the potentially present fish groups or only some in very exceptional hydrological situations can pass. Presence of a quite big obstacle without any fish pass/es or with little or non functional fish pass.

4.2. Fish pass effectiveness *in situ* estimation techniques

The most reliable way to check the effectiveness of a fish pass is the *in situ* indirect or direct estimation of the crossing rate for each species, defined as the number of fish per unit of time that overcome it.

Fish pass effectiveness was assessed using methods that allow estimation of the barrier effect on fish species present. The barrier effect was deducted from fish crossing rates, deviations of size frequencies in the water intake of the fish pass and downstream reach of the obstacle or deviations of size frequencies in reaches upstream and downstream of the obstacle (Lucas & Baras, 2001; Roni, 2005).

The evaluation of barrier effect was undertaken preferably (but not only) during high migration activity periods of the species expected to be present in each river stretch, so that the barrier effect was maximised. We assumed that a barrier effect would exist when fish crossing rates are different than the natural fish pass ability (assuming all sizes and species should be able to cross under natural conditions) and when deviations in size frequency distributions upstream and downstream of the obstacle are found.

Thus, fish pass effectiveness was based on estimating barrier effects through deviations in crossing rates and in size class frequencies and following the criteria below, focusing on upstream fish migration (equivalent to the same quality range established for river connectivity within the ICF index; Table 2, Solà *et al.*, 2011):

1. If all fish species and individuals present downstream of the obstacle can pass under nearly any hydrological situation and the fish species size frequencies downstream and upstream are equal, there is an absence of a barrier effect, representing natural conditions, and the fish pass effectiveness is of **very good quality**.
2. If the majority of the fish species and individuals present downstream of the obstacle can pass in nearly any hydrological situation and the fish species size frequencies downstream and upstream are similar, there is a small barrier effect, and fish pass effectiveness is **good**.

3. If the majority or some of the fish groups and individual specimens present downstream of the obstacle can pass, and the fish species size frequencies downstream and upstream are similar in any or in some hydrological conditions, there is a barrier effect indicating that the fish pass could be specific or not completely functional, and thus fish pass effectiveness would be classified as **moderate**.
4. If only one or few species and individual specimens present downstream of the obstacle can pass and the fish species size frequencies downstream and upstream are different, there is a barrier effect indicating that the fish pass could be very specific or poorly functional, and thus fish pass effectiveness would be classified as **poor**.
5. If none of the fish species or individual specimens present downstream of the obstacle can pass, or only some individual specimens can cross under very exceptional hydrological situations and the fish species size frequencies downstream and upstream are very different, there is a barrier effect indicating that the fish pass is non-existent or non-functional, and thus fish pass effectiveness would be classified as **bad**.

The application of different techniques to estimate fish crossing rates and deviations in size frequency was based on the type of fish community present and the characteristics of the studied river reach, obstacle and fishway.

Indirect estimation techniques

The techniques used consisted of methods such as comparison of fish populations on both sides of the obstacle using electrofishing procedures (Santos *et al*., 2006). Thus, depletion sampling with three passes was performed using Erreka III (Acuitec, Euskadi, SP) equipment with a Honda GXV50 motor (220 V, 50 Hz and 2,200 W: Lobón-Cerbiá, 1991; Travade & Larinier, 2002) at all the assessed sites.

Additionally, fish trapping systems (Travade & Larinier, 2002; Roni, 2005; Clavero *et al.*, 2006) were employed at four sites (HPW2, HPW3, GS3 and IW1), while mark-recapture methods (Larinier et al., 1994; Amstrup et al., 2005) were used at one site

(HPW1), and individual mark-recapture methods using passive induction transmitters (PIT tags; Roni, 2005; Amstrup et al., 2005) were used at two sites (GS3 and IW1).

Group marking with acrylic

Mark-recapture methods are widely used in many studies on animal biology and ecology (Larinier et al., 1994; Amstrup et al., 2005), especially focusing on migratory movements and, specifically, on barrier effects and fish pass efficiency. This method does not cause infection, and there is no increase in mortality or decrease in physical capacity if the marked individuals are longer than 0.12 m (Larinier *et al*., 1994).

The marking of migrating fish allows assessment of crossing rates through river obstacles by applying numerical models of marking and recapture, which are of varying complexity. A common limitation of these methods, apart from having an effective marking system, is obtaining sufficiently abundant samples because the recapture probability could be high enough and, indirectly, estimates that could arise could be sufficiently consistent. This probability is subject, of course, to the sample size of marked fish, but also to the real population where it is diluted. This usually limits marking and recapture studies to small populations or systems of modest dimensions. The tendency to make long journeys along the river axis makes it difficult to retrieve of migratory fish marked information, especially in medium-sized or large rivers. Several marking techniques are applicable.

Only on one site (HPW1), an injection of acrylic paint into fish fins was used (Fig. 6). This allows speed dialing and inexpensive control of large samples of fish, which can be released immediately. We marked different coloured fish caught on each side of the obstacle to be analysed (red downstream, blue upstream). Such labelling involves the problem that acrylic paint is absorbed or eliminated in a few months; and in summer, when the water temperature is high, it disappears in a few weeks.

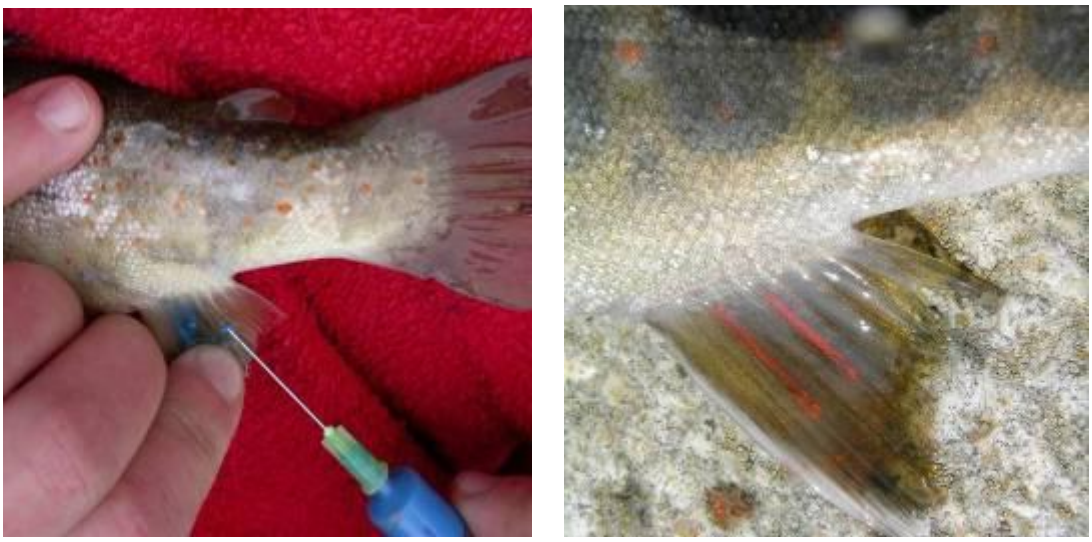

Figure 6. Procedure for the application of acrylic paint on the anal fin of a brown trout (*Salmo trutta*) in the Ter river at Camprodon (El Ripollès region). October 2006.

Its main purpose is the detection of fish that have crossed the fish pass having been marked and released downstream or upstream. They need to be recaptured by fish traps or electrofishing. Based on this data and the proportion of fish marked in the downstream and upstream subpopulation, it is possible to estimate crossing rates for species, which can be weighted by population size due to the obtained estimates through the parallel application of methods of depletion sampling for electrofishing.

Individual marking with PIT tags

PIT tags are, literally, passive integrated transponders. This is an alternative approach to group marking (Roni, 2005; Amstrup et al., 2005), consisting of a small electronic microchip encased in biocompatible glass cylinders (in this study, 2 mm thick by 12 mm long and operating at 134.2 kHz) which are inserted in the peritoneal cavity of fish (see Fig. 7). Being activated by a detector, fixed or portable, unique animal identification is done through radio frequency identification (RFID). Thanks to encapsulated micromarks carrying an individual alphanumeric identification code, this technique permits individually identifying each marked fish recaptured once again.

Being internal tags, the possibility of loss is minimal. They also have the advantage of not needing energy and, therefore, can be used to identify animals during very long periods. There are several models of reader antennas, which can be installed in rivers or channels, individually or in series. Each antenna is connected to a receiver that continuously records fish with PIT brands flowing through the assessed fish pass (see images in Fig. 8).

Its main purpose is the detection of fish that have crossed a fish pass having been marked and released downstream (or upstream). Based on this data and the proportion of fish marked in the downstream subpopulation, it is possible to estimate the crossing rates for species that can be weighted by population size due to the obtained estimates through the parallel application of methods of depletion sampling for electrofishing.

Moreover, the individual identification of each marked fish allows for accurate biometric characteristics of the specimens.

In this study, two antennas were installed in series at the water outlet downstream and at the entry upstream of the pool fish pass of the gauging station of the Llémena stream (GS3) to assess fish displacements between two fish passes (GS3 and IW1).

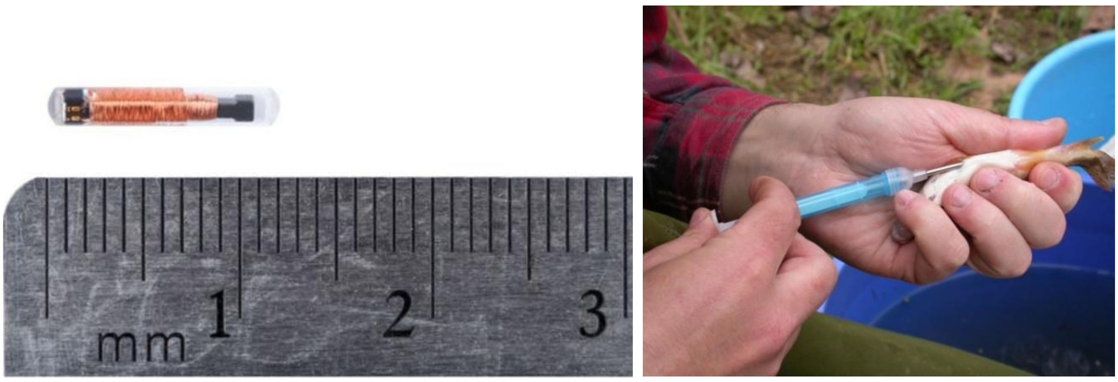

Figure 7. Procedure for the use of a PIT tag (left) in the peritoneal cavity of a Western Mediterranean barbel (*Barbus meridionalis*) in the Llémena stream at Ginestar de Llémena (Ter river basin, El Gironès region) (right). May 2010. Pictures: www.biomark.com/catalog/tags (left) and Marc Ordeix – CERM (right).

Figure 8. Location of the two rectangular antennas for continuous detection of PIT tags, installed in series, downstream and upstream of the pool fish pass at the gauging station of the Llémena stream at Ginestar de Llémena (Ter river basin, El Gironès region) (left), and emptying process of the data logger of the top antenna (right). 11th November 2010.

Direct estimation techniques

Two techniques have been used: installation of fish traps at the water intake of each assessed fish pass, and visual counts (Travade & Larinier, 2002; Marmulla & Welcomme, 2002).

Installation of fish traps at the water intake upstream of the facility

The installation of fish traps at the water intake of each assessed fish pass (Fig. 8) allows capture of all the fish that cross it. This is done with the aim of comparing fish crossing with potentially downstream fish migration population, obtained by using electrofishing systems (Fig. 9), mainly using fish crossing rates and/or deviations of size frequencies (Lucas & Baras, 2001; Roni, 2005). It is complemented by daily collection of hydrological and environmental data.

Ideally, traps should be installed while there is evidence of further possible movement of fish or, alternatively, for an entire year. Reviews need to be carried out daily, to count, measure, and finally release the fish caught. Thus, direct counts of the total number of migrants that use the fish pass are obtained. However, this is only possible for financially well-endowed projects, facilities with permanent staff or that also have a fish pass adapted for fish trap incorporation, permanent and easy maintenance and emptying.

Fish traps must be adapted to each fish pass. They should be checked daily and emptied to check their status and to clean them. In all cases, it is necessary to install a permanent mesh, arranged as a deflector and at a short distance upstream of the trap, to prevent trap blockage (with leaves or branches).

Figure 8. Special fish trap blocking the cross-sections of the fish pass of Les Rocasses weir, at Camprodon (Ter river, El Ripollès region) in October 2006 (top), and special fish traps blocking the cross-sections of the fish pass of the Torroella de Montgrí gauging station (Ter river, El Baix Empordà region) in May 2006 (bottom).

This method allows for obtaining a significant amount of information and a good approximation to the effectiveness of the analysed fish passes. Species composition and density and parameters such as size structure, cohort or age group and sex ratio were used to characterise the fish populations. At each site, the most abundant species were analysed to include a sufficient number of individuals to draw size distribution frequencies and perform statistical analyses.

Figure 9. Electrofishing in the Llémena stream upstream of the gauging station of Ginestar de Llémena (Ter river basin, El Gironès region) on 25th May 2010 (top), and procedure for weighing (bottom left) and measuring the fork length (bottom right) of Iberian redfin barbel (*Barbus haasi*) in the Merlès stream downstream of the Puig-reig gauging station (Llobregat river basin, El Berguedà region) on 20th October 2010 (bottom).

Visual counts

Despite being limited by water turbidity and the presence of a large number of migrating fish, visual counts (Travade & Larinier, 2002; Marmulla & Welcomme, 2002) have been done as well. This technique was only used at one site (at the gauging station of the lower Ter River; GS1).

Full censuses of a few minutes are repeated every hour or hour and a half throughout a day and while there is sufficient light. One possibility is to do this from the top of a bridge, but in any case the vision angle must be optimal. A complementary video recording is also recommended.

This census procedure is mainly limited to medium-sized or large fish (total length greater than 0.2 m) and is only applicable in very specific situations and always with a strong personal effort. In return, it is relatively inexpensive, and has no impact on the hydraulic system or on the dynamics of migratory fish.

5. When and why do Iberian freshwater fish migrate?

5.1. Introduction

Migration is a common phenomenon in many organisms, terrestrial as well as aquatic. All species of fish migrate at some time in order to successfully complete their life cycles. Migration is typically a seasonal event most often associated with, and as a prelude to, reproduction or feeding. Other behaviour of fish includes short term movements for other purposes; even daily periodic movements, concerning the alternating use of rest and activity zones found within the day to day living zone of the fish, and vertical migrations as well, can be considered forms of migration. Therefore, the term 'fish migration' is usually used for seasonal movements, daily movements and dispersion (Gough et al., 2012).

It includes all those fishes which live in or regularly enter fresh or low-salinity brackish water. Estuarine areas and brackish water are an integral component of freshwater drainage basins and a substantial number of predominantly freshwater species migrate into brackish environments (Lucas & Baras, 2001).

For a large number of species, seasonal reproduction mass-migration implies the synchronised meeting of a high number of mature fish of both sexes in the reproduction zones over a short period of the year (Lucas & Baras, 2001). It can include all the population (e.g. European eel (*Anguilla anguilla*)) or just a part, which occurs when just a fraction of a population migrates and the remainder are resident (e.g. big-scale sand smelt (*Atherina boyeri*) and European flounder (*Platichthys flesus*)). It may be both passive and active.

The nature of ontogenetic migration behaviour in freshwaters can be divided in two major groups (following McDowall, 1997):

a) **Potamodromous species** (or holobiotic potamodromous species), whose entire life cycle is completed in freshwater. Their migration can be lateral from river to floodplain (phytophilic species, like Northern pike and common carp, looking for vegetated areas in slow-moving waters), separated by small distances (which may be a few metres), or longitudinal, from lower river reaches, lakes or dams to running waters upstream, separated by small or large distances, moving through lakes, rivers and tributaries, looking for the very specific spawning grounds required to receive their roe (the majority, lithophilic species, e.g. most cyprinids), during several days or weeks.

b) Diadromous species (or amphialine species), whose life cycle is completed undertaking regular, seasonal and life-stage-consistent migrations between marine and freshwater environments (McDowall, 2008), separated by small or large distances, during several days, weeks or months. This comes in three distinct forms: anadromy, catadromy and amphidromy:

b1. <u>Anadromous</u> (or amphialin potamotocous) (e.g. salmons, sea trout and shads): some fish species that migrate from seas or oceans to freshwater to spawn (having completed in the sea their somatic growth, fully mature) and run down river principally to feed in the ocean or sea. The migration to the sea consists essentially of juveniles and, to a lesser degree, adults that have survived the reproductive process.

b2. <u>Catadromous</u> (or amphialin thalassotocous) (e.g. eels, flounders, sea basses and mullets): adult fish run downstream to the sea in order to spawn, and run up to the freshwater during the juvenile stage and colonise them to feed and mature.

b3. <u>Amphidromous</u>: several marine species that enter freshwater, with migration for prolonged feeding (postlarval to juvenile fish) or refuge. Fish born in freshwater/estuaries then drift into the ocean as larvae before migrating back into freshwater/estuaries to grow into adults and spawn. This is regarded as being very rare, possibly occurring in just a few Pacific fish species, but probably absent (Lucas & Baras, 2001).

Ontogenetic migratory behaviour of freshwater fish results from the separation in space and time of optimal habitats used for feeding and growth, sexual maturation, reproduction, during different life-history stages, refuge and/or survival. Therefore, migration up and down rivers and in and out of lakes or coastal lagoons, involves cyclic alternation between at least two, three (spawning, feeding and refuge) or more habitats, essential for the species to survive (Lucas & Baras, 2001).

In the tropics, the general pattern for reproductive potamodromous migration is an upstream spawning migration, followed by a downstream dispersion of eggs, larvae and adults into floodplain areas where growth and maturation occur (Carolsfeld et al., 2003). Adults move to spawn, juveniles move to disperse, sub-adults move to disperse and colonise, fish make diurnal movements between feeding and resting locations, fish move into side-streams to shelter from floods and also to spend the winter months. If fish of any species are prevented from making any of these movements then it is likely to have adverse consequences for the success and survival of both the individual and the population of that species. A more subtle consequence can be a threat to the population from a reduction in genetic fitness caused by fragmentation (Armstrong et al., 2010).

Migration is associated with internal (ontogenic changes) and external (food availability, predator avoidance, displacement and climate) causes (Lucas & Baras, 2001). Native fish migrate for different reasons or factors needed for their conservation, including spawning, dispersion, feeding, refuge and displacement (Armstrong et al., 2010). In detail, they are:

a) **Spawning**: to enhance lifetime reproductive success mostly with great accuracy in spawning areas in which they originated (homing), suitable for reproduction at a time when other sexually mature fish are present (Wooton, 1990). This is the most well-known reason for migration: fish invariably migrate for the purpose of reproduction, a fundamental part of their life cycle strategy.

b) **Dispersion**: larvae, fry, and juveniles have to move to disperse and colonise. For them, drift is an indispensable natural phenomenon of fundamental biological importance (Baudoin et al., 2014). The dispersal of fingerlings depends mainly on the density of the population. If the density is high, their dispersion will be greater (Feunteun et al., 2011). That’s important for metapopulation conservation. The term drift is most commonly used for movements from upstream to downstream; however, it also corresponds to the transport of European eel leptocephali from the Sargasso Sea to the coasts of Europe and North Africa via the Gulf Stream.

c) **Feeding**: fish may make regular movements to feed at appropriate environments for each species, following a diurnal pattern, a small scale 'daily movement', perhaps without a clear need or aim as fish move between refuges and feeding areas or to avoid predators. Diel scale of movement is far more important to survival and growth for larval and juvenile fishes, with tiny energy reserves and high susceptibility to predation, than for larger fishes (Lucas & Baras, 2001). Rest and activity zones are often habitats that differ widely in their hydromorphological characteristics. The range, direction and frequency of these active movements are variable depending on the species involved, on individual fish, on the stage of development within a given species, and on the season and environmental conditions (Baudoin et al., 2014).

   Sometimes fish can swim large distances when looking for food, to the most productive environments, depending on demand of the species, population size, availability of food and environmental conditions. The ecological relevance of estuarine nursery function in supporting marine adult subpopulations of fishes based on the use of segregated habitats during early life stages is a key ecological feature of these species: adults inhabit the marine environment and, after spawning, larvae/post-larvae/juveniles enter shallow coastal areas and estuaries, where they spend the first months or years of life, benefiting from high food availability, water temperature and refuge from predators, until returning to the marine environment. The economy of energy for catadromous fish includes spending less energy for osmoregulation in freshwater than at sea (Feunteun et al., 2011). Fish expansion towards feeding grounds and thus the diminution of intraspecific competition in limited reaches also could benefit their metapopulation (Levins, 1969). Where there is massive migration of diadromous fish between freshwater ecosystems and the sea, there is also an ecologically significant import and export of nutrients (McDowall, 2008).

d) Refuge: fish undertake movements that could be classified as migration to escape threatening environments, to avoid acute adverse conditions, often seasonal in nature, including floods, low river flow and seasonal drying of river sections, high water temperatures, low oxygen concentrations, pollution or other unwelcome physiological challenges. Migrants can also benefit by evading predators. Catadromous fish reduce the risk of being preyed on: there are fewer predators in freshwater than in the sea (Feunteun et al., 2011). It is hypothesised that migration is an adaptive behaviour in response to seasonal changes in predation (P) and growth (G) and that migrating fish change habitat (i.e. between lake and river) so as to minimise the ratio between predation mortality and growth rate (P/G) (Brönmark et al., 2008).

e) Displacement: fish may get moved passively, being displaced downstream by pollution or being washed downstream by drift, floods or other events. They then need to move to re-colonise areas once the event has passed. Such non-periodic active movements are generally followed by a return of the fish to the original site, but significant mortalities may occur (Baudoin et al., 2014). Furthermore, there is a strong tendency for diadromous species to be much more widely distributed and exhibit little genetic structuring across their widespread populations than non-diadromous species; diadromous fish, by migrating from the sea, invade fish communities in streams and lakes affected by historical events like volcanism and glaciation, and have restored their populations to these areas (McDowall, 2008).

Migrations do not take place at the same time for all species, even if spring and autumn are the main periods. Migrations may in fact be observed throughout the year if all species living in certain rivers or river reaches are taken into account (Baudoin et al., 2014).

For any one species the intensity of migration will usually follow a seasonal pattern. This will vary depending on exactly where in the catchment area any obstruction is located, e.g. far up the system or low down it. Migration at some life-stages, particularly for spawning and dispersion, can occupy quite small windows of time (Armstrong et al., 2010).

Methods by which fishes exhibit movements towards particular spatial goals are highly variable and may be strongly influenced by spatial scale (Lucas & Baras, 2001). Migration is thought to evolve in response to seasonal changes in food availability, predation risk, weather conditions and climate change (Rochard & Lassalle, 2010).

Within an evolutionary context, the “selection” of cues by fishes may be regarded as due to specific receptors or discrimination capacities being selected during the evolution of the species or populations exposed to different environmental pressures and stimuli (Lucas & Baras, 2001). It has been widely reported that the principal factors which influence fish migration behaviour include sexual maturity and condition of fish, water temperature, river flow, currents, hydrology and meteorology, diurnal/nocturnal rhythm or photoperiod, electric and magnetic fields. In addition, the range of cues used by fishes during their migration is very wide and these movement patterns are changeable, being related to other environmental variables like tidal cycle, large oceanic features, moonlight, turbidity, salinity, water quality, and other imprinted or inherited information on a route, as described below:

a) **Sexual maturity and condition of fish**: the prespawning season is associated with high levels of sex hormones, which are correlated with a high responsiveness to stimuli, including home stream water (Hasler & Scholz, 1983). The thyroid hormones may alter the responsiveness of fish in prolonged navigation and homing (Lucas & Baras, 2001). Also, the more mature and the lower condition of the fish, the lower its swimming ability is likely to be (Armstrong et al., 2010).
b) **Water temperature**: apart from the physiological effects that it has on fish swimming speed, water temperature can also act as a trigger for fish migration (Armstrong et al., 2010). For example, water temperature and other specific environmental factors, such as the photoperiod and oxygen level, are used by the European eel (*A. anguilla*) (Bruijs & Durif, 2009).

c) **River flow, currents, hydrology and meteorology**: fish will tend to move in windows of opportunity, rarely in a drought or a flood. Coarse fish, for example, will be moving upstream to spawn in the spring when flows will usually be within a certain range around Annual Daily Flow (ADF). Changes in river flow can act as a stimulus to fish to migrate, responding to rising river discharges, and also falling river discharge following a spate (Armstrong et al., 2010). As has been observed in mature silver European eel, following the final stages of metamorphosis, the downstream migration of juvenile sea lamprey (*Petromyzon marinus*) is also triggered by an increase in discharge in rivers, and at night (Kelly & King 2001).

d) **Tidal cycle**: some age groups or species, like glass eel (*A. anguilla*) and larvae of European flounder (*P. flesus*), colonise coastal, estuarine and river habitats using selective tidal stream transport, by stemming ebb tides (or taking refuge) and swimming or drifting on flood tides (McCleave & Wipplehauser, 1987).

e) **Diurnal/nocturnal rhythm or photoperiod**: migration patterns may demonstrate a diurnal rhythm. Examples include salmon smolts migrating downstream mostly at night, at least early on in the migration season (later they migrate by day and night), and adult lampreys (Armstrong et al., 2010). Shad migrate during the day (Armstrong et al., 2010).

f) **Electric and magnetic fields**: water movement across the earth's magnetic field may induce electric currents, which though tiny may affect the selection of migration direction and navigation of numerous fish species (Formicki et al., 2002), e.g. salmonids such as Atlantic salmon (*Salmo salar*) (Rommel & McCleave, 1973), European sturgeon (*Acipenser sturio*) (Nelson et al., 2103) and European eel (*A. anguilla*) (Tesch et al., 1992).

g) **Large oceanic features**: described by winter NAO (North Atlantic Oscillation), GSI (Gulf Stream Index) and PEA (Potential Energy Anomalies) indexes, they may, for example, affect the migration of leptocephalus larvae of European eel (*A. anguilla*) to the continental shelf (Bonhommeau et al., 2009).

h) **Lunar cycle**: the migration of several fish species is highly correlated with New Moon periods, e.g. for small cyprinids (Baird *et al.*, 2003), European eel (*A.*

anguilla) (it is well known that eels are strongly photophobic, and a full moon inhibits migration; Bruijs et al., 2003) and brown trout (*S. trutta*) (Slavík et al., 2012).

i) Turbidity: migrations mainly occur during night and twilight periods (Prignon *et al*., 1998).

j) Salinity: an ability to detect differences in salinity is an important component in orientation mechanisms of the diadromous fish (Lucas & Baras, 2001). Water salinity significantly influences the presence or absence of some fish species, e.g. marine species in coastal lagoons and estuaries. There is also clearly great plasticity and adaptability of migratory behaviour between freshwater and saline environments in many fish species, and the movement of "primary" freshwater species into brackish and coastal waters deserves greater consideration than it has received to date (Lucas & Baras, 2001).

k) Water quality: changes in water quality may be due to natural factors such as deoxygenation of water in inundated forest areas, as leaves decompose, or acid flushes on naturally acidic upland. Other variations in water quality may be due to anthropogenic influences such as wastewater discharges. In many cases, deterioration of environmental conditions on a seasonal or diel cycle triggers emigration of fish from what was previously an appropriate habitat (Lucas & Baras, 2001). Water quality may also control connectivity between essential habitats. In macrotidal estuaries, Estuarine Turbidity Maxima (ETM) has a strong impact on water quality because of the low oxygen concentration occurring as a response to the related high bacterial and low photosynthetic activities. Using an acoustic telemetry array, trans-estuarine migration of allis shad (*Alosa alosa*) in the Loire River (France) is inhibited during hypoxic episodes in the middle part of the estuary. Trans-estuarine migration occurs hastily during neap tide when the ETM decreases, both in terms of spatial extent and intensity, inducing a shift in a set of covariates including dissolved oxygen, which increases, and suspended matter, which decreases (Tétard et al., 2016).

l) Other imprinted or inherited information on a route: the so-called "innate" component of homing (any return to a particular point or area within a hypervolume) might reflect fish having evolved slightly different sensory capacities, and being capable of sensing different concentrations or combinations of environmental cues (Lucas & Baras, 2001). Thus, most fishes can utilise the sun for orientation during migration. Visual cues are undoubtedly important for piloting in familiar areas, following local landscape features (Lucas & Baras, 2001). Vision is also fundamental to much behaviour, such as predator avoidance and feeding, and also directed movement (Lucas & Baras, 2001). Likewise, olfaction is an extremely important imprinted component for fishes. Distinct components of the Atlantic salmon (*S. salar*) homeward migration are: the first oceanic phase is rapid and highly directed, probably involving navigation or orientation using the position of the sun and reference to the Earth's magnetic field (Hansen & Quinn, 1998); the final phases of up-river migration are thought to involve the sense of smell to detect olfactory cues that are remembered from the outward migration (Hasler & Scholz, 1983). This has also been reported for European sturgeon (*A. sturio*) (Nelson et al., 2013), sea lamprey (*P. marinus*) (Teeter, 1980), and European eel (*A. anguilla*) (Westin, 1990; Righton et al., 2012; Wysujack et al., 2015).

Freshwater fish diversity in the Iberian Peninsula is characterised by a high degree of endemicity (73% of species are endemic to the Iberian Peninsula; Maceda-Veiga, 2013) and restricted distribution ranges. A high percentage of Iberian species are unique for the biodiversity of the planet: converted into a biogeographical island by the Pyrenees mountain system (N) and the Straits of Gibraltar (S), isolation gave rise to present-day Iberian endemisms. Of all the families with an Iberian distribution, those of greatest evolutionary radiation are Cyprinidae (with most endemisms) and Cobitidae (Granado-Lorencio, 1996; Doadrio, 2001).

The Iberian Peninsula has a long history of anthropogenic disturbance that has led to the poor conservation status of its ichthyofauna, with 52% of species catalogued as critically endangered, endangered or vulnerable, according to UICN criteria (Maceda-Veiga, 2013). Populations are declining sharply (Hermoso & Clavero, 2011).

However, Mediterranean fish migration has not been much studied. The causes could be the absence of commercial and sporting species (except brown trout and salmon), and also possibly the low diversity of continental ichthyofauna, compared with others (Doadrio, 2001).

Iberian fish have developed optimal adaptive strategies for survival over time (population structure, time of reproductive maturity, mortality rates, feeding, spatial movements, etc.). This ecosystem-species coevolution has given rise to very characteristic life cycles in the fish fauna, so that their behaviour patterns in the hydrological regime of these rivers are similar. Such behaviour is one of typically altricial life styles: that is, a short life, rapid growth, early sexual maturity and early reproduction, high fecundity, and high reproductive investment, and the possibility of multiple reproductions, together with a certain degree of opportunism and generalism in their diets (Encina et al., 2006).

In the Mediterranean, diadromous fish were present in the past. However, some are now extinct (e.g. European sturgeon (*A. sturio*)) and the population of most others has greatly decreased (Doadrio, 2001). In the last hundred years the Iberian Peninsula has become one of large volumes of dammed waters. It has passed from a predominance of lotic environments to one of lenitic environments, with all that entails for certain organisms, which have evolved through geological eras adapting life strategies, metabolic types, capacities of resource use, etc. in contexts – rivers – diametrically opposed to those of the ecological context in which human activity has led them to act (Encina et al., 2006).

Likewise, under a climate change scenario, it is expected that by the end of the 21st century several species, such as Atlantic salmon (*S. salar*), brown trout (*S. trutta*), European flounder (*P. flesus*) and sea lamprey (*P. marinus*), among others, will show a great decrease in the Iberian Peninsula (Lassalle et al., 2009a), disappearing from several basins. Populations in the southern distribution of these species are inherently at risk of extinction because in the southern basins, where water availability is often critical during the summer period, activities such as water abstraction accentuate droughts and also pollution has an impact by diminishing the dilution capacity of streams.

The small cyprinid species so typical of Iberian river ecosystems (chub, barbels, loach, etc.) cannot live in reservoirs, not only because of the many problems inherent to a reservoir, but also because of their demanding requirements regarding reproduction, substrates, physico-chemical conditions, etc. Nor can those species making trophic or reproductive migrations from the sea (such as sand smelt and eel), which become trapped in the reservoir and die out with the passage of time. There is no evidence to date that any reproduce in reservoirs: all need to reproduce in rivers or sea. To close their life cycle, they must at least migrate during the spawning period, as is the case of barbels, nase and trout, among many others. Only exotic species, such as common carp (*Cyprinus carpio*), black bass (*Micropterus salmoides*), sunfish (*Lepomis gibbosus*) and mosquitofish (*Gambusia holbrooki*), among others, are able to reproduce in Iberian reservoirs, although another question concerns the success of their egg-laying, which is very sensitive to the frequent changes in level caused by water management (Encina et al., 2006).

Certain species, such as European river lamprey (*Lampetra fluviatilis*), brook lampreys (*Lampetra alavariensis*, *Lampetra auremensis*, *Lampetra lusitanica* and *Lampetra planeri*), Atlantic salmon (*S. salar*) and sculpins (*Cottus hispaniolensis* and *Cottus aturi*), or forms such as sea trout (*S. trutta* morpha *trutta*) are not found in Iberian Mediterranean river basins. Others, such as sea lamprey (*P. marinus*), allis shad (*Alosa alosa*) and European flounder (*P. flesus*), are less common in Iberian Mediterranean basins than in the Atlantic ones. Even though certain environmental components of the Atlantic basins (e.g. tides, a higher degree of marine productivity and colder water) are absent in the Mediterranean, common patterns in the periods and possible causes of fish migration in Iberian freshwaters may be reported.

The objective here is to study fish migration in Iberian – and Mediterranean – freshwaters to justify the promotion of connectivity improvements for fish (dam removal and/or fish pass projects) in rivers, lakes and coastal lagoons, and their effective management. Understanding nature is the only way to manage it ecologically (Granado-Lorencio, 1996).

5.2. Methods

Study area

The Iberian Peninsula is a large peninsula in southwestern Europe, between the Pyrenees and North Africa, between the Mediterranean Sea and the Atlantic Ocean. It covers 582,925 km^2. The nature of the environmental matrix of Iberian rivers (Western Mediterranean; Fig. 10) is characterised by strong, frequent, and unpredictable fluctuations, both intra- and inter-annual. The most important characteristic of their predominant Mediterranean climate river systems is their intermittence, with periods of torrentiality and of drought. In these river environments, fish communities are dominated by cyprinids (Granado-Lorencio, 2000).

Furthermore, snowmelt and transitional Iberian rivers also exist (in the Pyrenees and the Cantabrian Mountains, among others), characterised by high summer flow and lack of supply in the cold season, and Atlantic climate rivers likewise, mainly located along the western and northern coasts (wetter and cooler). Their native fish communities comprise salmonids: brown trout (*S. trutta* morpha *fario*) and, occasionally, sea trout (*S. trutta* morpha *trutta*) and Atlantic salmon (*S. salar*), except in Mediterranean river basins.

Species diversity increases along the river from the upper reaches towards the estuary: this is a consequence of an increase in habitat heterogeneity, a greater capacity to buffer perturbing phenomena down-river, and the incorporation of estuarine species in the last stretch (both slackwater-tolerant species and amphidromic or diadromic ones) (Granado-Lorencio, 2000).

Figure 10. Study site in the Western Mediterranean and Western Palearctic. The biggest rivers of the Iberian Peninsula are shown.

According to UICN, the main threats to Iberian ichthyofauna are water extraction (including hydrological infrastructures) and introduced species, followed by climate constraints, pollution and overexploitation (Maceda-Veiga, 2013; Antunes et al., 2016). These threats are shared with other Mediterranean regions (Hermoso & Clavero 2011).

After the building of many dams in the 19th and the 20th centuries, upstream migration became blocked at the lower stretches of all major rivers, interrupting the movement of migrating fish along most of the main stream and principal tributaries. Habitat fragmentation and reduction by construction of large dams, weirs and other man-made barriers are among the main threats to fish populations in the Iberian Peninsula (Cabral et al., 2005; Doadrio, 2001). For instance, mainly due to river fragmentation by dams, it has been estimated that there is an 80% loss of accessible habitat for lampreys (Mateus et al., 2012) and over 80% loss of accessible habitat for European eel (*A. anguilla*) (Clavero & Hermoso, 2015), historically widespread throughout the Iberian Peninsula.

The number of weirs and dams with fish passes is extremely low in the Iberian Peninsula, and only a small percentage of them are still functional (Santo, 2005; Elvira et al., 1988; Ordeix et al., 2011).

Data collection

We collected information on all native freshwater fish species of the Iberian Peninsula (Kottelat & Freyhof, 2007; Doadrio et al., 2011), including the last described new species (e.g. Mateus et al., 2013) (Table 3).

Not included in this review is the long list of marine adventitious species which only appear in estuarine zones when environmental conditions and salinity are particularly suitable, and marine seasonal species which only occur in estuaries when salinity conditions are favourable.

We reviewed a significant portion of the available information (publications and databases) of freshwater fish biology and ecology and fish pass assessments in spawning and migrating periods, and other possible associated causes of migrations, for the whole Iberian Peninsula.

Table 3. List of the native freshwater fish families and species of the Iberian Peninsula.

Syngnathidae	**Cyprinidae**	**Cobitidae**
Syngnathus abaster	*Achondrostoma arcasii*	*Cobitis calderoni*
Petromyzontidae	*Achondrostoma occidentale*	*Cobitis paludica*
Lampetra alavariensis	*Achondrostoma oligolepis*	*Cobitis vettonica*
Lampetra auremensis	*Achondrostoma salmantinum*	**Homalopteridae**
Lampetra fluviatilis	*Anaecypris hispanica*	*Barbatula quignardi*
Lampetra lusitanica	*Barbus haasi*	**Gasterosteidae**
Lampetra planeri	*Barbus meridionalis*	*Gasterosteus aculeatus*
Petromyzon marinus	*Gobio lozanoi*	**Cyprinodontidae**
Cottidae	*Iberochondrostoma almacai*	*Aphanius baeticus*
Cottus hispaniolensis	*Iberochondrostoma lemmingii*	*Aphanius iberus*
Cottus aturi	*Iberochondrostoma lusitanicum*	**Valenciidae**
Acipenseridae	*Iberochondrostoma olisiponensis*	*Valencia hispanica*
Acipenser sturio	*Iberochondrostoma oretanum*	**Blenniidae**
Clupeidae	*Luciobarbus bocagei*	*Salaria fluviatilis*
Alosa alosa	*Luciobarbus comizo*	**Gobiidae**
Alosa fallax	*Luciobarbus graellsii*	*Pomatoschistus microps*
Anguillidae	*Luciobarbus guiraonis*	**Mugilidae**
Anguilla anguilla	*Luciobarbus microcephalus*	*Chelon labrosus*
Atherinidae	*Luciobarbus sclateri*	*Mugil cephalus*
Atherina boyeri	*Parachondrostoma arrigonis*	*Liza ramada*
Salmonidae	*Parachondrostoma miegii*	*Liza saliens*
Salmo salar	*Parachondrostoma turiense*	*Liza aurata*
Salmo trutta	*Phoxinus bigerri*	**Pleuronectidae**
	Pseudochondrostoma duriense	*Platichthys flesus*
	Pseudochondrostoma polylepis	**Moronidae**
	Pseudochondrostoma willkommii	*Dicentrarchus labrax*
	Squalius alburnoides	
	Squalius aradensis	
	Squalius carolitertii	
	Squalius castellanus	
	Squalius laietanus	
	Squalius malacitanus	
	Squalius palaciosi	
	Squalius pyrenaicus	
	Squalius torgalensis	
	Squalius valentinus	

5.3. Results

Currently, Iberian freshwater fish are composed of 19 families and a total of 69 species (Table 3); almost all of them (95.7%; 66 species from 17 families; Table 4) clearly migrate. The great majority are potamodromous species (70.0%; 49 species from 6 families), and also include diadromous species (25.7%; 18 species from 9 families), subdivided as anadromous (10 species) and catadromous (8 species), here considering the two morphs of brown trout as different species (Fig. 11). Strictly, amphidromous species are absent. Only 2 families include several species with two different migratory patterns: Petromyzontidae and Salmonidae, potamodromous (brook lampreys and brown trout) and anadromous species (sea lamprey, salmon and sea trout) (Table 2). One species superimposes two different migratory patterns, depending on their morphs: brown trout (*S. trutta* morpha *fario*), potamodromous, and the marine form of brown trout, named sea trout (*S. trutta* morpha *trutta*), anadromous, except in Mediterranean river basins (where it is absent). Likewise, the three-spined stickleback (*Gasterosteus aculeatus*) is potamodromous around the Iberian Peninsula, not catadromous as occurs in northern Europe (Fernández et al., 2015).

Only a few species (4.2%; 3 species in 2 families) living in Mediterranean coastal lagoons, Baetican toothcarp (*Aphanius baeticus*), Iberian toothcarp (*Aphanius iberus*) and samaruc (*Valencia hispanica*), do not have a clear migration pattern apart from circadian movements. Anyway, there is some kind of connection between Iberian toothcarp (*A. iberus*) local populations of the Mar Menor lagoon (Murcia region, Spain) and a perimeter of approximately 45 km: several individuals were found sporadically in the islands inside the lagoon (Oliva-Paterna, 2006; Oliva-Paterna & Torralva, 2008). In addition, genetic structure and flow between these populations has been confirmed (González et al., 2015).

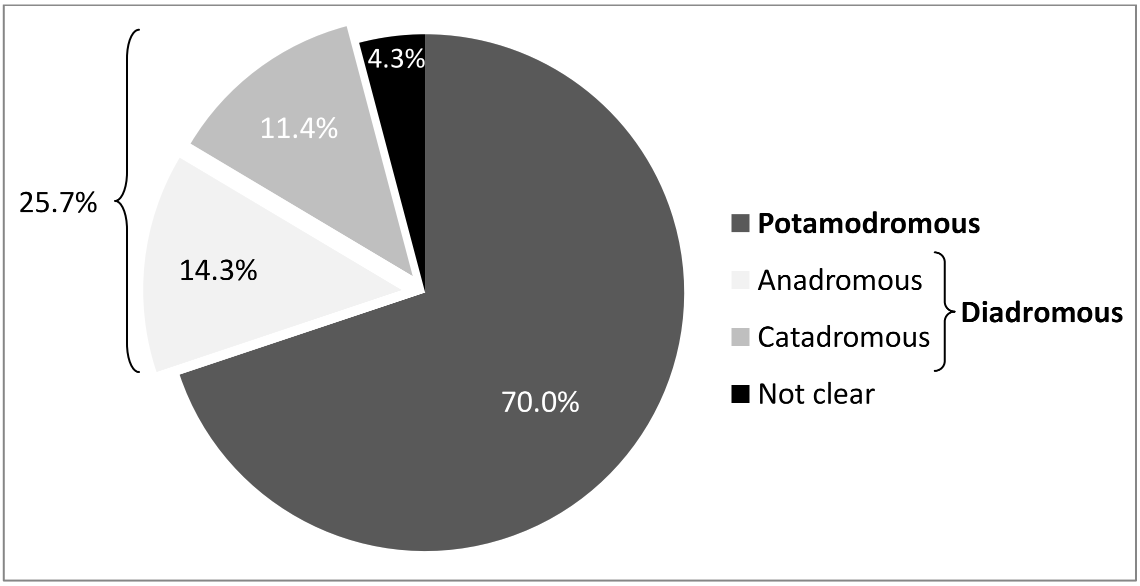

Figure 11. Migration behaviour of Iberian native fish species, divided in two major groups: potamodromous and diadromous (subdivided into anadromous and catadromous) species.

Table 4. Incidence of migrating behaviour within families of Iberian freshwater fishes*.

(*) The two morphs of brown trout (*S. trutta* morpha *fario* and *S. trutta* morpha *trutta*, respectively potamodromous and anadromous) are here considered as though different species.

Family and common name	Number of species	Number of potamodromous species	Number of diadromous species	% of migratory species
Syngnathidae (pipehorses)	1		1	100
Petromyzontidae (lampreys)	6	4	2	100
Cottidae (sculpins)	2	2		100
Acipenseridae (sturgeons)	1		1	100
Clupeidae (shads)	2		2	100
Anguillidae (eels)	1		1	100
Atherinidae (silversides)	1		1	100
Salmonidae (salmons and trouts)	3	1	2	100
Cyprinidae (barbels, chubs, etc)	36	36		100
Cobitidae (loaches)	3	3		100
Homalopteridae (river loaches)	1	1		100
Gasterosteidae (sticklebacks)	1	1		100
Cyprinodontidae (killifishes)	2			0
Valenciidae (Valencia killifish)	1			0
Blenniidae (blennies)	1	1		100
Gobiidae (gobies)	1		1	100
Mugilidae (mullets)	5		5	100
Pleuronectidae (flounders)	1		1	100
Moronidae (temperate basses)	1		1	100
TOTAL	70	**49**	**18**	**95.8**

When

Available information depends on species, especially, but not only, on socio-economic interest. Information is especially for upstream fish migration. The most important fish migration periods of native Iberian freshwater fish are (Table 5):

a) **Spring and early summer for pipehorses, cyprinids, shads, sturgeons, flounders and European sea bass**. Around March-April, 51.9% of the total observations of Iberian barbel (*Luciobarbus bocagei*), and 77% of Iberian nase (*Pseudochondrostoma polylepis*, in Lima River (N Portugal; Santos et al., 2004). There is an exception downstream of the Touvedo dam in the same Lima River (N Portugal), where upstream movements of native cyprinids mostly occur in summer and early autumn (Santos et al., 2014).

   European flounder (*P. flesus*) and European sea bass (*Dicentrarchus labrax*) enter estuaries in early and late spring (Martinho et al., 2008), respectively. European flounder (*P. flesus*) is a winter spawner (Teixeira et al., 2010) and European sea bass (*D. labrax*) is a spring spawner (Jennings & Pawson, 1992), both into the sea. They use estuarine and other shallow water areas as feeding and nursery grounds during summer. A migration by the largest young European flounder occurs only at the end of winter. The largest juvenile sea bass already migrate to coastal areas by the end of summer; migration pulses of older fish can also occur throughout the year.

   In addition, in the north-west of the Iberian Peninsula, catches of allis shad (*A. alosa*), first, and twaite shad (*Alosa fallax*), after, decline from January at sea, a phenomenon that can be understood as the onset of migration to the rivers (Nachón et al., 2015). The greatest catches of allis shad occur in the upper part two months later than in the lower part, and one month later in the case of twaite shad in the Ulla River (Galicia, NW Iberian Peninsula). Twaite shad starts entry to the Ebre river estuary from February to March; to spawn upstream in the Ebre river from May to June (López et al., 2015). Young-of-the-year (YOY) seaward migration takes place in schools, during summer and autumn, and before one year of age.

b) **Autumn, winter and spring for salmonids**. In the Ulla River (Galicia, NW Spain; Caballero, 2013), Atlantic salmon (*Salmo salar*) starts to enter the river in March, but they do not go upstream to spawn until October. Downstream migration is December-April. There, sea trout (*S. trutta* morpha *trutta*) start to enter a little late, in April, and they go upstream to spawn in October.

   Brown trout (*S. trutta* morpha *fario*) generally go upstream to spawn in autumn or winter; much earlier in the year at higher latitude and altitude due to low water temperatures and longer incubation periods (Gortázar et al., 2007). In SE Spain, they can spawn from October to early May (Larios-López et al., 2015). Brown trout mainly ascend in spring (57.9%) in the Lima river (N Portugal; Santos et al., 2004), although some seasonal activity persists in autumn (18.3%).

c) **Late autumn, winter and early spring for the European eel and sea lamprey.** Although a minimum of glass eel (*A. anguilla*) recruitment occurs throughout the year everywhere, a clear seasonal pattern was observed: upstream for glass eel and elvers mostly occurs in October-March (April) in northern Spain (Lara, 1994; Lobón et al., 1995), October-April (May) in northern Portugal (Domingos, 1992; Antunes & Weber, 1996), October-May in southern Spain (Arribas et al., 2012), and October-March in Catalonia (Gómez et al., 2012), including a secondary peak in June in the Ebre delta (López et al., 2015).

   In the Guadalquivir estuary from June to September (mean glass eel density 0.09 individuals/m^3 in August), whereas higher recruitment was observed from October to May (mean glass eel density 1.91 individuals/m^3 in December), density tending to peak twice a year: in autumn/winter and spring respectively (Arribas et al., 2012), coinciding with the Gulf of Cadiz (Arias & Drake, 1990).

   Upstream movements of yellow (young) European eels are mostly in summer in the Ebre river, Catalonia (Aparicio et al., 2012), and summer and early autumn in the Lima river, Portugal (Santos et al., 2014). Downstream migration of yellow eels is also frequent in summer, with a peak in June/July, in the Ulla river (Galicia, NE Spain; Cobo et al., 2014). Downstream migration of silver (mature) eels varies depending of the year, but normally it occurs in autumn, mainly around October in the Ulla river (Cobo et al., 2014) and the northern Costa Brava streams

(Catalonia) (author’s unpublished data), and until March in a Cantabrian river (N Spain; Lobón-Cerviá & Carrascal, 1992).

Sea lamprey (*P. marinus*) initiate their upstream reproductive migration in Portuguese river basins in December, with peak of spawning migration between February and April and spawning between May and June, depending on the meteorological conditions (Almeida et al., 2000, 2002). Following the final stages of metamorphosis, downstream migration typically occurs between November and April (Hardisty & Potter, 1971).

d) **All through the year (except late autumn and early winter) for mullets**. In spring and summer many adults and in summer many juveniles of mullet species (thinlip grey mullet (*Liza ramada*), flathead grey mullet (*M. cephalus*) and thicklip grey mullet (*Chelon labrosus*)), enter estuaries and rivers (Ordeix et al., 2011; Aparicio et al., 2013). Conversely, March corresponds to the seaward migration of some seasonal migrant species, namely golden grey mullet (*L. aurata*), in the Aveiro coastal lagoon (Pombo & Rebelo, 2002). The spawning season of thinlip grey mullet (*L. ramada*) extends from September through January, in pelagic waters (Koutrakis et al., 2011). Fish fry approach the shore in dense schools and enter lagoons, rivers, or even lakes, where they continue to grow. Most juveniles of thinlip grey mullet (*L. ramada*) enter rivers in the summer (Aparicio et al., 2012; Aparicio et al., 2013). When grey mullet approach sexual maturity, they move again towards the sea, where maturation is completed and spawning takes place.

Their spawning periods can also vary considerably between years, mainly depending on river discharge and water temperature: this accounts for the 25% variation in Iberian nase (*P. polylepis*), and just temperature 21% variation in brown trout (*S. trutta*) and 17% variation in sea lamprey (*P. marinus*) in N Portugal (Santos et al, 2004). Water temperature (13%) and rainfall (17%) also account for variation in flathead grey mullet (*M. cephalus*).

Most Iberian freshwater fish migrate before and after the spawning period, but they also move a lot outside these periods.

Why

Very few studies of the Iberian Peninsula contain at the same time information on fish movements, spawning periods and other possible causes for fish migration. Therefore, the information for this review has mainly been obtained separately.

Daily movements, associated to home range, are short. For example, the distribution of estimated home ranges for Iberian redfin barbel (*Barbus haasi*) captured in a small tributary of the Llobregat river (Catalonia) showed most of the fish (55.1%) moved <20 m. The mean home range was 54 m^2. Only 1.8% of fish had home ranges above 250 m (Aparicio & Sostoa, 1999). Other home ranges reported in a stream of southern Iberia (Prenda & Granado-Lorencio, 1994) were slightly longer: 129–131 m (560–1752 m^2) for Andalusian barbel (*Luciobarbus sclateri*), 63–107 m (282–1434 m^2) for Iberian nase (*Pseudochondrostoma polylepis*) and 60–119 m (254–1842 m^2) for Iberian chub (*Squalius pyrenaicus*).

Important movements have been mostly clearly associated with the particular spawning periods of native Iberian freshwater fish (e.g. eel, salmonids, cyprinids, sturgeon and shads) and they have been extensively collected (Table 5). In addition, some groups which spawn in marine environments and come to estuaries, rivers or coastal lagoons, probably searching for food, and grow in these more productive and less salty environments than the sea (e.g. mullets and sea bass), have also been widely collected (Table 5).

As an example of migration associated to feeding, in the Minho estuary (N Portugal), European flounder (*P. flesus*) densities are maximal in less haline areas, coinciding with a decrease of the abundance of brown shrimp (*Crangon crangon*), important prey of estuarine fish, until extremely low densities (Freitas et al., 2009).

As a clear example of migration related with refuge, the jarabugo (*Anaecypris hispanica*), a small endemic Iberian cyprinid in small tributaries of the Guadiana river basin (SW Spain and S Portugal; Sousa-Santos et al., 2014e), undertakes movements to avoid acute adverse seasonal conditions and droughts of river sections. It is adapted to extremely Mediterranean rivers: water courses that have large variations in water regime throughout the year, with torrential rains during autumn and winter and a semi-arid summer period. It looks for mean water temperatures of 25°C, resisting up to 30°C (Salvador, 2009). In winter, it goes upstream to spawn. In summer, it moves to the lower stretches downstream, searching permanent river flow or pools.

Dispersion and displacement have not been much studied.

The principal cues or factors which influence fish migration behaviour of Iberian freshwater fish migration are: sexual maturity and condition of fish, diurnal/nocturnal rhythm or photoperiod, water temperature, river flow, water currents or hydrological conditions, tidal cycle in estuaries, meteorological conditions, large oceanic features, moonlight, turbidity, salinity and water quality. The possible relationship between electric and magnetic fields and imprinted or inherited information on a route with Iberian freshwater fish migration has not yet been assessed in this area.

Sexual maturity and condition of fish

For most Iberian freshwater fish, the reproductive period is particularly long and variable from year to year. Females can spawn various times each year. Their spawning and migrating periods are extended and change between years, adapting these periods to the great year variability (i.e. of rainfall and water temperature) that is characteristic of the Mediterranean climate.

Contrary to several northern European species (*S. salar*, *A. alosa* and *P. marinus*) (Travade & Larinier, 2002), which are endangered or have already disappeared from Mediterranean basins, most Iberian and Mediterranean fish species have multiple spawning (*A. sturio*, *A. fallax, Anaecypris hispanica*, *Aphanius iberus*, *A. boyeri*, *Barbus haasi*, *Barbus meridionalis*, *Cobitis paludica*, *Cobitis calderoni*, *Gobio lozanoi*, *Iberochondrostoma lemmingii*, *Luciobarbus microcephalus*, *Luciobarbus comizo*, *L. bocagei*, *Luciobarbus graellsii*, *Luciobarbus sclateri*, *Luciobarbus guiraonis*, *Salaria fluviatilis*, *S. trutta, Squalius alburnoides*, *Squalius pyrenaicus* and *V. hispanica*, among others).

There are some differences between sexes during migration periods. Before disappearing, in the lower Guadalquivir (SW Spain), at the end of January and February, more than half of European sturgeon (*A. sturio*) going upstream were males (50-55%), and from the first days of March the ratio began to change in favour of females, which in May were more than 90% (Classen, 1944). Likewise, in the lower Minho river (Portugal), more males of allis shad (*A. alosa*) than females were caught in March and April, and more females than males between May and July (Mota et al., 2015).

Water temperature

In the Touvedo fish lift on the Lima river (N Portugal; Santos et al., 2002), water temperature is the most important factor stimulating the upstream movement of cyprinids in spring, namely Iberian barbel (*L. bocagei*) and Iberian nase (*P. duriense*); they start to migrate at water temperatures above 15°C and 12-14°C, respectively. Iberian barbel and Iberian nase also move upstream of the Santa Teresa reservoir, in the Tormes River (Duero Basin, Spain; Sanz *et al*., 2013), at water temperatures above 15°C and 17°C, respectively.

Sea lamprey (*P. marinus*) migrate in N Portugal (Santos et al., 2004) at temperatures above 11°C, showing pronounced activity at 12–16°C. In the Sella river (N Spain), sea lamprey spawn at 13-16°C (Rodríguez-Muñoz et al., 2001).

In the Lima river (N Portugal; Santos et al., 2002), brown trout migrate from 9 to 22°C, mainly in spring and autumn, when water temperature exceeds 13°C. In NE Catalonia (Ordeix et al., 2011; Ordeix, 2015), brown trout (*S. trutta*), Catalan chub (*Squalius laietanus*), Western Mediterranean barbel (*B. meridionalis*), Iberian redfin barbel (*B. haasi*) and thinlip grey mullet (*L. ramada*) move upstream when the water temperature rises (5, 13, 10, 8 and 10 degrees respectively for each species), and high passage rates are associated with warmer water (12°C for brown trout, 14.5°C for thinlip grey mullet and 14-18°C for Catalan chub and Western Mediterranean barbel). A water temperature of about 18°C is the cue for maturation of oocytes of Iberian roach (*S. alburnoides*) in the Guadiana river, Portugal (Ribeiro et al., 2003).

The main seasonal activity of flathead grey mullet (*M. cephalus*) in N Portugal (Santos et al., 2004) does not begin until early spring in association with warmer water above 13°C, and the greatest increment is observed in summer months at temperatures above 21°C. Similar results have been reported for thinlip grey mullet (*L. ramada*) in the Tagus river, Portugal (Oliveira & Ferreira, 1997), the Ter river (Ordeix et al., 2011) and the Ebre river (Aparicio et al., 2012), Catalonia.

River flow, currents, hydrology and meteorology

Most Iberian fish move to return to their home area just after high or moderate peak flows. In the lower Guadalquivir river, Spain, the abundance of European sturgeon (*A. sturio*) was directly correlated with the magnitude of river flow (Fernández-Pasquier, 2000), and in the Mondego estuary, Portugal, glass eel (*A. anguilla*) abundance is favoured by high river flows (Domingos, 1992). Downstream migration of silver (mature) eels around October follows peaks with the increase in flow in northern Costa Brava streams (Catalonia) (author's unpublished data).

Freshwater fish from the Iberian Peninsula follow seasonal changes in their occupation of the space in rivers and streams throughout the annual cycle: during periods of floods, the drag from the rising water causes the fish to drift, until they find shelter in zones down-river such as pools, etc. Species, depending on their capacities and on chance, are distributed at random. Later, when the flow has decreased, the populations go upriver, recolonising the devastated stretches. Whereas the process of drifting is random and unspecific, and affects all the species and cohorts, that of recolonisation is determined by each species and its swimming and jumping abilities. During low water, when the water level is minimum they are concentrated in pools, with conditions of overcrowding, nocturnal anoxia, and in some cases, generalised mortality. The individuals that survive this period of environmental stress colonise the river in the following period, causing a demographic explosion of the species that are attempting to occupy the newly recreated space (Encina et al., 2006).

Tidal cycle

Spatial changes in glass eel density within the Guadalquivir estuary (Andalusia, Spain; Arribas et al., 2012) depend on tidal and light situations, though maximum densities were mainly observed at diurnal and/or nocturnal flood tides.

Diurnal/nocturnal rhythm or photoperiod

Movements of fish are mostly at night: Iberian barbel (*L. bocagei*), Iberian nase (*Pseudochondrostoma polylepis*), Iberian chub (*Squalius carolitertii*), brown trout (*S. trutta*) and sea lamprey (*P. marinus*) show significant nocturnal preferences in their upstream movements in the Lima river (Portugal; Santos et al., 2004). Peak movement is generally between 19.00 and 23.00 hours for cyprinids and trout, with the maximum between 19.00 and 20.00 hours, corresponding to 18–24% of the daily total, whereas sea lamprey ascend mainly late at night (22.00–03.00 hours).

A study of local movements of European eel (*A. anguilla*) in a small lake in southwestern Spain (Doñana National Park, Huelva province) using radio telemetry showed that they covered a larger area at night than during the day, with an average of 23% and 42% of activity region used during the day and at night respectively (Labar et al., 1987). They were also more active during days with rainy and cloudy weather and used a larger total area than during drier, more stable weather.

Nonetheless, some species have a clear preference for moving during the day: diurnal upstream movements are significantly more intense for flathead grey mullet (*Mugil cephalus*), with hourly activity taking the form of a bimodal curve with its maxima in the early morning (08.00–10.00 hours) and mid-afternoon (15.00–17.00 hours) in the Lima river (Portugal; Santos et al., 2004). Similar information have been reported for thinlip grey mullet (*L. ramada*) moving upstream in the Ter river (Ordeix et al., 2011), Catalonia.

Large oceanic features

A positive nonlinear effect of the winter North Atlantic Oscillation (NAO) on the rate of brown trout (*S. trutta*) population growth has been observed in Navarra (N Spain; Alonso et al., 2011). The presence of some age groups or species, like glass eel (*A.*

anguilla), varies significantly from one year to another: long-term (inter-annual) changes have been positively correlated with oceanic factors related to recruitment success (NAO index and primary production at the spawning area) and also local environmental factors (westerly and southerly wind mixing indexes and rainfall) in the southernmost European estuaries (Spain; Arribas et al., 2012).

Moonlight

The biggest catches of glass eel (*A. anguilla*) in estuarine fisheries in Catalonia occur mostly during new moon phases, but they are also positively influenced by wind, large river flows and mild temperatures (Gómez et al., 2012). In the Fluvià river (NE Catalonia), statistically significant differences between Full Moon and New Moon activity of Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) were also observed (Ordeix, 2016).

Turbidity

Low water turbidity explains the distribution of several fish species in rivers: the big-scale sand smelt (*A. boyeri*), which is also associated with high salinity (Sostoa et al., 1990), although it is a fish that tolerates the lack of salinity of the water, even freshwater (Kottelat & Freyhof, 2007)) appears related to turbidity in the Ter and Daró estuaries, in Catalonia (Aparicio et al., 2013). Pombo et al. (2005) also associate the presence of big-scale sand smelt with high turbidity areas in the Aveiro estuary, in Portugal. In addition, glass eel (*A. anguilla*) upstream migration is clearly associated with high turbidity – followed by high rainfall, low or moderate water temperatures and low salinity – in the Guadalquivir estuary (Arribas et al., 2012).

Salinity

Water salinity, often measured as electrical conductivity, shows a longitudinal gradient of variation along Iberian rivers that allows us to separate marine species, near the sea or river mouths, from those freshwater species found strictly in river stretches. Freshwater estuaries contributions vary seasonally with salinity, temperature and oxygen, among other parameters. This significantly influences the presence or absence of certain species: thus, many marine species only enter estuaries when conditions are favourable to take their food resources (i.e. juveniles of European pilchard (*S. pilchardus*) and European anchovy (*Engraulis encrasicolus*) in the coastal lagoons of the Ebre delta, Catalonia (Sostoa & Sostoa, 1979)) and return to the sea when physical and chemical conditions are no longer appropriate. Areas with a higher degree of salinity, spring (May in the Aveiro estuary, Portugal) is characterised by the massive recruitment of marine schooling species, like European pilchard (Pombo & Rebelo, 2002). It is also the case of golden grey mullet (*Liza aurata*), which lives in autumn in the Ter estuary and several coastal streams of the Costa Brava area, in Catalonia, coinciding with the period in which the conductivity tends to be higher (maximum around 27400 µS/cm, from Aparicio et al., 2013; and between 806 and 53500 µS/cm, from author's unpublished data).

Several more strictly coastal species (thinlip grey mullet (*L. ramada*), big-scale sand smelt (*A. boyeri*), common goby (*Pomatoschistus microps*), black-striped pipefish (*Syngnathus abaster*) and European flounder (*P. flesus*), among others), which spawn in the sea, only enter the Ebre river and estuary sporadically, in spring and summer, coinciding with the period of minimum flow of rivers, when the water is most salty (40-60% of saturation; Sostoa et al., 1990). In addition, salinity is considered the main factor structuring small-bodied fish assemblages in hydrologically altered coastal lagoons of the Ebre delta (Catalonia; Rodríguez-Climent et al., 2013): the dominant species is the common goby (*P. microps*) when the lagoons reach highest salinity values, whereas juvenile mullet (leaping mullet (*Liza saliens*) and golden grey mullet (*L. aurata*)) and the Iberian toothcarp (*A. iberus*) increase constantly with salinity.

In the lower Guadalquivir river (S Spain), salinity accounted for 50% of the variance in the number of species, whereas salinity and temperature were the environmental variables that controlled macrofaunal abundance and biomass (Baldó et al., 2005).

The species that use estuaries as a nursery, European sea bass (*D. labrax*) and sand smelt (*A. presbyter*), dominating in the Aveiro estuary (Portugal), among others, occur at low salinity values (Pombo & Rebelo, 2002). There, the fish richness is highest in summer: it is the case of the Aveiro (Pombo & Rebelo, 2002) and the Ter and Daró estuaries (Aparicio et al., 2013), among others (Moyle & Cech, 2003). However, the presence of some marine species is sometimes limited in time, and in some cases their presence is not significant, as might be the case of a low abundance of European flounder (*P. flesus*) in the Ter estuary (Aparicio et al., 2013).

In the freshwater tidal area of the Minho estuary (N Portugal) (Morais et al., 2011), a low salinity area, European flounder arrive from higher salinity or freshwater areas to spawn. Then the eggs could hatch in a brackish environment, combining active migration strategies and selective tidal stream transport, contradicting the general assumption that European flounder reproduce exclusively in marine waters (Martinho et al., 2008).

Water quality

Only reported for a non-native species, the common carp (*C. carpio*), diel vertical migration patterns, mostly in the warm season, shifting from deep positions near the bottom during the night (with extensive use of hypoxic waters (<1.1 mg/L dissolved oxygen) and decreased activity) to shallow waters during the day, has been proposed as a mechanism to avoid catfish (*Silurus glanis*) predation risk in the Flix reservoir, in the Ebre river (Catalonia) (Benito et al., 2015).

5.4. Discussion

Potamodromous fish are predominant, and diadromous are divided between catadromous and anadromous almost equally, as occurs in temperate regions (Lucas & Baras, 2001). The 18 diadromous native species (and 52 non diadromous ones) in the Iberian Peninsula (582,925 km^2) are among the 28 diadromous fish species that were present in Europe, North Africa and the Middle East in historical times (Lassalle et al., 2008), and broadly equivalent to 38 diadromous species (and 62 non-diadromous ones; Scott & Crossman, 1973) in Canada (9,984,670 km^2) and 17 diadromous species (and 24 non-diadromous ones, depending on decisions about taxonomic status of some lineages; McDowall, 2008) in New Zealand (166,940 km^2). All of them are part of the relatively small number of around 250 diadromous fish species in the world (McDowall, 2008).

When

Because of a latitudinal gradient regarding the timing of migration, southern populations start their upstream migration earlier in the year than northern populations (Mennesson-Boisneau *et al.,* 2000). And the southern spawn before the northern. For example, the Minho allis shad (*A. alosa*) population starts migration earlier in spring (in March, exceptionally in January) than northern European populations and later than Moroccan populations (Mota et al, 2015). Also, allis shad starts its spawning migration one month before twaite shad (*A. fallax*), and allis shad show a longer migration period and greater fluctuations in catches and the start and end of migration shows notable interannual variations that were repeated cyclically, compared with twaite shad (Nachón et al., 2015).

This is also the case of European sturgeon (*A. sturio*): historically, spawning takes place in spring from April to May in the Gualdalquivir river (S Spain; Classen, 1944), from March to June in the Po river (Italy; Pavesi, 1907), slightly earlier in the Tyrrenian rivers (D'Ancona, 1924) and early summer (May to June) in the Gironde (France) and between June and August in the Elbe river and its tributaries such as the rivers Eider, Oste and Stör (Germany; Rosenthal et al., 2010).

Among others, the spawning season of European flounder (*P. flesus*) has a latitudinal gradient, with later spawning at higher latitudes. In northern Europe, flounder spawn at the end of spring (Van der Veer, 1985), while on the northern French, Spanish and Portuguese coasts spawning occurs mainly in the winter (Teixeira et al., 2010).

Conversely, brown trout (*S. trutta*) spawning migration starts much earlier in the year at higher latitude and altitude (Gortázar et al., 2007).

Seasonal migrations of Iberian fish are sometimes extensive but can be short: both can be manifested in irregular ways, as is typical in the Mediterranean climate. In short, coinciding with other areas of central and southern Europe, and in the United Kingdom (Armstrong et al., 2010) and France (Porcher & Travade, 2002; Baudoin et al., 2014), Iberian and Mediterranean freshwater fish migration periods, both upstream and downstream, occur the whole year round.

There is not much difference in cooler latitudes: taken over several years, runs in salmon rivers may cover the whole year depending upon when the hydroclimatic conditions are favourable to migration (Porcher & Travade, 2002). The pronounced peak for salmon (*S. salar*) caught at the Kerhamon station (River Elorn, France) in the months of May, June and July corresponds to the arrival of grilse (salmon which stay only briefly at sea, characteristic of the rivers of the Armorican Massif). However, migration activity is maintained all year round, with some fluctuation in intensity.

In estuarine areas, very few fish are present in winter (between December and March-April). They stay in the sea or rivers, where temperature and salinity are more stable and warmer. Starting from April, fish diversity and density increase with the appearance of fry mainly coming from the marine environment (Feunteun et al., 2011). In addition, estuarine fish follow a daily migratory rhythm around each home range and, except in Mediterranean basins, there is a colonisation of salt marshes and mudflats at each high tide (twice daily), where fish come to feed.

Because of the wide range of species present, there are only very short periods of time, or none, when fish passes are not necessary or should not be in operation. This may occur in the upper zones of certain catchment areas not reached until shortly before the spawning period of salmonids, for example. However, whatever the reason may be, free passage must be guaranteed as soon as migrators begin to arrive at an obstruction (Porcher & Travade, 2002).

The overlapping migratory periods of the many species present in large rivers makes it necessary to maintain permanent passage at obstructions (Porcher & Travade, 2002). In any one river system where migratory salmonids, eels and other species are present, migration both upstream and downstream may be taking place virtually the whole year round (Armstrong et al., 2010). Fish passes must always be operational.

Attempts to pass obstructions without a fishway (or with a badly designed one) can cause injuries or mortalities amongst the migrating fish population. Observations made on elvers and small eels blocked downstream of a dam have also shown that they can suffer a high mortality rate from predators (Porcher & Travade, 2002). The failure of just one fish pass facility on the migratory route is enough to totally ruin all other concerted efforts to maintain or develop stocks. A watercourse being developed to re-establish unrestricted passage must therefore be a watercourse that must be closely and permanently monitored. It can no longer be regarded as a natural system and must be actively managed (Porcher & Travade, 2002).

Why

Movement is one of the most important capabilities of animal behaviour as it allows response to the conditions of the environment to increase growth, enhance survival and reproductive success of individuals, in the first instance, and whole species, by extension (Kahler et al., 2001). In most Iberian freshwater fish species, habitat requirements are different for each life stage (egg, larva, juvenile or adult), so individuals need to occupy and move between different habitats throughout their life.

Only in very specific situations, it has been considered that migration may not be essential (except at metapopulation scale). It is possible that, if fish have good feeding conditions and reproduction in the area or section where they live, they will not tend to make long journeys. This could be the case of Mediterranean coastal lagoons occupied by toothcarps, and small rivers and streams with varied hydraulic and geomorphological conditions, in the upper part of the Pyrenees, Catalonia, where brown trout (*S. trutta*) have a highly sedentary behaviour (Sostoa *et al*., 1995).

There is information available on reasons for native Iberian freshwater fish migration: associated to spawning periods and, only for some species, feeding and refuge.

Extended and multiple spawning period

The reason why most Mediterranean freshwater fish have multiple spawning and their spawning period is extended and changes between years, could be that they adapt their reproduction to the great year on year variability (i.e. of water temperature and rainfall) that is characteristic of the Mediterranean climate. It seems that this tactic has advantages in fluctuating environments, since progeny are not at risk in just one reproductive event when a climatic catastrophe could destroy all spawning in a particular year (Cambray & Bruton, 1984). For example, it is suggested that an extended reproductive period for brown trout (*S. trutta*) is also an advantage in a highly unpredictable hydrological regime such as the River Castril (Granada, S Spain; Gortázar *et al*., 2007).

Associated to temporary or semi-permanent rivers, species like the freshwater blenny (*Salaria fluviatilis*), which in Iberian basins has a spawning period from the end of May to the beginning of August (Vinyoles, 1993; Vila-Gispert & Moreno-Amich, 1998), coincide with the driest period in the Iberian Peninsula. This may force this species to select those zones with more permanent water availability, usually found going downstream (Filipe *et al*., 2002).

Regarding the differentiation of sizes and sexes during migration, following patterns as described for European sturgeon (*A. sturio*) in S Spain (Classen, 1944), and allis shad (*A. alosa*) in Portugal (Mota et al., 2015) and also in France (Baglinière et al. 2003), among other species, one reason may be that males, in many cases, of smaller size and requiring less effort than females to produce their gametes, act as pioneers or leaders. Thus, adult lamprey females are subsequently attracted to the spawning grounds by sexual pheromones (bile acids) released by mature males, the first to arrive and begin nesting activities (Hardisty, 1986).

Feeding

Most Iberian fish go up-river in spring in an ecological and evolutionary effort to maximise efficiency in the exploitation of trophic resources. During a certain period of the year (usually from February to June, depending on the species and the river), populations go up the tributaries in search of zones of clear, well-oxygenated water with beds of sand or gravel on which to lay their eggs (Rodríguez-Ruiz & Granado, 1992; Encina & Rodríguez-Ruiz, 2002). The most important reason why most Iberian fish migrate in spring is that a large number of the progeny have to hatch in summer, when in Mediterranean rivers a high production of small prey is available, proliferating at slower flow and constituting one of the main components in the diet of the fry of many species, such as cyprinids. At the same time, the risk of spates, and thus the loss of the spawn, is minimal in this period. Lastly, high temperatures favour rapid growth of the young of the year (YOY) (Encina et al., 2006).

Catadromous fish, e.g. eel and mullets, do not require upstream ascent to strictly complete their life cycles. However, upstream passage, or entry to a coastal lagoon, of a critical number of individuals could benefit their metapopulation by allowing expansion towards upstream feeding grounds and thus diminishing intraspecific competition in downstream reaches. Better osmoregulation conditions than in the sea can also favour them (Feunteun et al, 2011).

Likewise, in spring many adults and in summer many juveniles enter estuaries and rivers to feed and grow: this temporal pattern is similar in several Mediterranean estuaries (Koutrakis et. al. 2000). Although some mullets spawn at sea (Kottelat & Freyhof, 2007), during their juvenile stages, including adults of several species, they enter coastal lagoons, estuaries and rivers looking for a protected area with abundant food that will provide favourable conditions for their development (Verdiell, 2009). Although there is no doubt about the role played by salinity in the distribution patterns of the family, some authors have hypothesised that the high trophic overlap found among young mullets determines their survival in low resource conditions and the species dominance can be explained by a possible trophic competition (Gisbert *et al.,* 1995; Cardona *et al.,* 2008).

Upstream, in small tributaries, most adults can't feed, and they must leave, and the competition between YOY and adults is less than in the central and lower parts of the rivers. The aim is to optimise the reproductive process (that is, perpetuate the species, and persist; Granado-Lorencio, 1992).

Many marine species enter estuaries when conditions are favourable only to take their food resources, and return to the sea when the physical and chemical conditions are not suitable (Blaber, 2000). The contrasting directions of migration can largely be explained by the availability of food resources in ocean and freshwater habitats. At a global scale, oceans are more productive than freshwaters in temperate latitudes, and anadromous species predominate. In contrast, catadromous species generally occur in tropical latitudes where freshwater productivity exceeds that of the ocean (Gross, 1988). In Normandy (N France), sea trout (*S. trutta* morpha *trutta*) females, which invest more energy in reproduction (genital products) than males, are more common than males migrating to the ocean, where food resources are more abundant than in freshwater (Feunteun et al., 2011). This situation is totally opposite in the Mediterranean, and in addition to other environmental constraints such as water temperature, this can lead to the absence of this migration behaviour in brown trout in their basins.

Furthermore, migrating fish upstream of reservoirs and large rivers are an important contribution to food for other species, such as the otter, in the Iberian Peninsula (Ruiz-Olmo et al., 2002).

Refuge

Most Iberian freshwater systems are intermittent, including periods of torrentiality and of drought. As has been indicated for the jarabugo (*A. hispanica*) in the Guadiana river basin (SW Spain and S Portugal; Salvador, 2009), probably most Iberian and Mediterranean fish undertake migrations to avoid seasonal drying of river sections or lagoons, high water temperatures, low oxygen concentrations, intraspecific competition and predation.

Combination of environmental factors associated with fish migration behaviour

Interactions between stimuli can always be considered; it is a more efficient strategy for fish than responding to a single cue (Lucas & Baras, 2001). The principal factors apply both to up- and downstream influence on fish migration behaviour of Iberian fish depending on species and migrating pattern. Water temperature, river-discharge events or water level, and light are environmental variables that influence fish migration and the intensity of the migration itself, among others. For example, until 1 October, the mobility of brown trout (*S. trutta*) in a tributary of the River Meuse basin (Belgium) showed restricted movements: daily journeys never exceeded 300m and corresponded to displacements by high floods or to routine home range movements. From 7 October to 15 November, most brown trout travelled upstream over distances from 5.6 to 22.95 km, into tributaries and sub-tributaries, and this was found to be triggered by the combination of several environmental factors: high variations of water temperature and water level over consecutive days, within a thermal range of 10–12°C (Ovidio et al., 1998).

Water temperature, among others

The brown trout (*S. trutta*) breeding population is at the greatest latitude and altitude sooner in the year due to low water temperatures and longer incubation periods (Gortázar et al., 2007): November-January in the Pyrenees (Sostoa et al., 1990; Mayo-Rustarazo et al., 1995); December-February in Asturias (N Spain; García & Braña, 1988), and in the Baetican mountains (SE Spain; Gortázar et al., 2007; Larios-López et al., 2015), where reproduction is between October and early May. In the Lima river (Portugal), most important movements of brown trout upstream are concentrated in spring, although they also take place in autumn (Santos et al., 2004).

The exception downstream of the Touvedo dam, in the Lima river (N Portugal), is for native cyprinids mostly migrating in summer and early autumn (Santos et al., 2014); this could be associated with the altered regime, cooling water, as happens downstream of other large Mediterranean dams, for example, on the Ter and Ebre rivers, Catalonia (Prats et al., 2012).

Water temperature is an important factor initiating up- and downstream migrations of several fish species. In particular, this may be the case in rivers where freshets do not regularly occur at the time when the environmental shift is favourable (Jonnson, 1991). Also outside the Iberian Peninsula, there is a broad consensus that water temperature is a very important environmental factor for the ascent of fish, e.g. salmonids, especially in spring and autumn (Jensen & Aass, 1995). Mature brown trout (*S. trutta*) undertake their upstream spawning migration at a time when temperatures become suboptimal and no longer enable fast growth (Ovidio et al., 1998).

The threshold for active migration upstream of Atlantic salmon (*S. salar*) (at least past obstructions) appears to be around 5°C, while for elvers it is 6-8°C, for small yellow eels (*A. anguilla*) around 13-14°C, and for many species of coarse fish it is about 9-10°C (Lucas, 1998). Conversely, there may also be upper limits above which fish will not migrate. Migratory salmonids will not migrate at temperatures above 21°C, while coarse fish are unlikely to migrate at temperatures over 28°C (Armstrong et al., 2010).

Coinciding with the data from Iberian systems, water temperature also appears to be an important determinant of sea lamprey (*P. marinus*) migration. In NW France, sea lamprey migrates upstream between March and June, when the water temperature is higher than 8-10°C (Porcher & Travade, 2002).

Several migration peaks of glass eel arrival are common in many estuaries and depend on two main factors: the reproductive period and the water temperature (Laffaille et al., 2007). A water temperature of 6°C is considered as a limiting factor for glass eel (*A. anguilla*) entrance into the Gironde estuary, SW France (Beaulaton & Castelnaud, 2005). Reproduction could explain the two observed migration peaks in the south of the Iberian Peninsula (Arribas et al., 2012; Arias & Drake, 1990) and on Mediterranean coasts (Gandolfi et al., 1984; Lefebvre et al., 2003). Although reproduction occurs in the Sargasso Sea during the entire year, the main reproductive peak is in spring (McCleave, 1993). It has been suggested that the western part of the Sargasso Sea favours successful transatlantic migration to all latitudes of the adult range in Europe and North Africa, which could explain the winter peaks observed along European coasts (Kettle & Haines, 2006). However, it has also been hypothesised that there is an additional transatlantic migration route from the north-east corner of the spawning region toward southern Europe and North Africa (McCleave, 1993), which could explain the second migration peak. Oceanographic changes have also been suggested to be one of the causes of the substantial annual fluctuations in recruitment in European and American eels (Moriarty & Dekker, 1997). Similarly, annual variations in European eel recruitment have been related to primary production (PP) in the spawning area (Bonhommeau et al., 2008) and to the North Atlantic Oscillation (NAO) winter index, which may force changes in fronts and currents that affect spawning and larval survival (Friedland et al., 2007).

Although most authors have found that there is a glass eel recruitment period from winter to spring along the European Atlantic (Elie & Rochard, 1994; Desaunay & Guerault, 1997) and Mediterranean coasts (Gandolfi et al., 1984; Ciccotti et al., 1995), there is a time delay between northern and southern regions (Zompola et al., 2008; Arribas et al., 2012.). This geographical shift may be explained by the latitudinal cline found in the timing of glass eel arrival at the different zones of the continental shelf (Tesch, 2003). Furthermore, since low water temperatures reduce the locomotive activity of glass eels (Elie & Rochard, 1994; Edeline et al., 2006), the latitudinal differences in their recruitment period to estuaries could also be related to differences in seasonal temperature patterns along the European coast. Similarly, on the Mediterranean coast, glass eel inshore migration shows a lag between western (autumn) and eastern regions (winter). This time delay in the arrival of glass eels could be explained by the time the larvae need to drift from Gibraltar to the most eastern regions (2000 km to Egypt) (Arribas et al., 2012).

Coinciding with many Iberian estuaries (Aveiro, Guadalquivir, Ebre, Ter), in the two Macedonian (Greek) estuaries species richness and total abundance also were found to increase during the warm seasons of the year (summer and autumn), following water temperature fluctuations almost immediately. The seasonality of temperature changes determines the temporal changes of species composition of the overall fish community (Koutrakis et al., 2000). Several fishway assessments (Santos et al., 2005; Ordeix et al, 2011; Aparicio et al., 2012) reported that the number of mullets ascending a fish pass increases in warmer months, when main upstream migrations of this species occur (Oliveira & Ferreira, 1997).

River flow, currents and freshwater availability

Changes in river flow and water current may influence when fish migrate, providing visual, tactile and inertial cues (Lucas & Baras, 2001). High water discharge may stimulate river ascent, also in lakes, estuaries and coastal environments, often mixed with additional stimuli (temperature, photoperiod, etc.) to concert movement in a single direction. To be carried downstream, fish must position themselves within the water column and actively swim out of sloughs and backwaters.

It has been hypothesised that increasing flows may have a positive influence on glass eel upstream migration (Gandolfi et al., 1984). Intense rainfall also reduces salinity values, and glass eels swim driven by positive rheotaxis towards low salinity water (Tosi et al., 1989). This behaviour can be enhanced by the existence of an odoriferous cue in freshwater caused by the presence of eels (Miles, 1968) or traces of geosmin (Tosi & Sola, 1993) in continental waters. Thus, an increase in rainfall, erosion and flow could change the composition of the dissolved or particulate components of the water and elicit the migratory response (Arribas et al., 2012).

The temperature, the cumulative water discharge from the channel in the five nights before the catch (freshwater lure) and the time that the drainage pumps were working accounted for the glass eel catches in the fish-pass in the Grau de la Fourcade. These are the main factors that could explain the variations in the catches of glass eel entering the Vaccarès coastal lagoon system (Rhône delta, S France). These results show that it is important that the lagoons should continue to receive rainfall runoff from their watersheds so that their water levels are high in winter, and that there is a good colonisation by glass eels as a result of a freshwater lure effect, when strong north winds expel low salinity water to the sea (Crivelli et al., 2008).

Conversely, the spawning migration of Atlantic salmon (*S. salar*) can be interrupted by low river flows, and may not resume until the flows recover or at the onset of imminent maturation (Gough et al., 2012). 48% of the annual variation in Atlantic salmon smolt production in the River Orkla, Norway, could be explained by egg deposition, a minimum daily discharge during the previous winter and a minimum weekly discharge during the summer three years before smolt migration. In spite of higher than natural winter discharges, minimum winter discharge is still a determinant of smolt production (Hvidsten et al., 2014).

During ontogeny, migratory fish in different life history stages are also transported downstream by the water flow. Therefore, silver (mature) European eel (*A. anguilla*) migrate downstream between autumn and winter, following peaks with the increase in flow (Travade & Larinier, 2002; Cobo et al., 2014; author's unpublished data). This coincides with other studies, i.e. in a Norwegian river, associated with the migratory behaviour of seaward migrating silver European eels (by transplanting tagged silver eels upriver after catching them in a trap at the outlet of the river). The number of days to median day of recapture of each batch decreased as the season progressed and decreased with increasing water discharge (VØllestad et al., 1994). Water temperature and day length (i.e. time at release) did not explain any of the remaining variation in the model.

Tidal cycles

Concerning daily upstream movements of mullets (flathead grey mullet (*M. cephalus*) and thinlip grey mullet (*L. ramada*), in the Lima (Portugal; Santos et al., 2004) and Arno rivers (Tuscany, Italy; Torricelli et al., 1982), two observed peak passages (early morning and mid-afternoon) have been related to tidal movements. Estuarine fish colonise rivers, salt marshes and mudflats at each high tide (Feunteun et al., 2011). The situation is not clear in Mediterranean river basins, where tides are practically imperceptible and these peak passages have also been observed (Ter river, Catalonia; Ordeix et al., 2011).

The variation of the vertical movements of glass eel (*A. anguilla*) through the water column takes into account cloud cover, lunar phases, the alternation of days and nights and water turbidity in the Gironde and Adour estuaries, France (Prouzet et al., 2009).

Diurnal / nocturnal rhythm or photoperiod

Migrations of juveniles and adults are mainly nocturnal, but sometimes diurnal (Jonnson, 1991). In addition, some fish spawn at night: allis shad (*A. alosa*) and twaite shad (*A. fallax*). Most Iberian cyprinids show significant nocturnal preference in their upstream movements (Santos *et al*., 2004; Sanz *et al*., 2013), e.g. brown trout (*S. trutta*) and sea lamprey (*P. marinus*).

Nocturnal preferences in upstream movements have been observed for most fish species (Jonsson, 1991), particularly cyprinids (Lucas et al., 2000; Santos et al., 2002) and salmonids (Aarestrup et al., 2003), and could be related to an avoidance of visual predators at that time of the day when survival is expected to be highest (Jonsson, 1991). At night chances of survival from visual predators are presumably higher: when migration occurs during hours of darkness this is an expected adaptation to avoid visual predators (Jonnson, 1991). Probably this is also a reason why Mediterranean fish move especially at night, e.g. European eel (*A. anguilla*; LaBar et al., 1987) and Western Mediterranean barbel (*B. meridionalis*; Poncin, 1994). Following eels by radio telemetry, it was observed that on cloudy or rainy days they were more active (LaBar et al., 1987). Also sea lamprey movements occurred during hours of darkness, which is in accordance with the findings of other authors (Almeida et al., 2002). And also common carp (*C. carpio*): while laboratory studies have focused on visual cues and short range, it is likely that wild carp were using olfactory cues because water clarity was poor and key movements occurred at night (Bajer et al., 2010).

Downstream migration as part of juvenile dispersion mainly takes place at night, partly as a predator avoidance response but also because in juvenile fish the mechanism for orientation is not immediately in place (Pavlov et al., 2002). Furthermore, a study on the behaviour of European silver eels (*A. anguilla*) in the open Atlantic Ocean and Sargasso Sea, indicated that predation may be a relevant factor even in the open north-eastern Atlantic Ocean. However, there was definitely no common direction chosen by eels. If the mechanism of homing towards the spawning ground is based on imprinted or inherited information about a route, the translocation of eels over several thousand kilometres could result in the fish failing to find their way. In general, there are still many open questions about the orientation of eels in the ocean. There is evidence that eels have the potential to use magnetic sense during migration (Durif et al., 2013). However, when released in the ocean, eels did not choose a common direction, which could indicate that other factors or cues may be important: thermal fronts or changes in physical or chemical characteristics of the water could be potential candidates (Wysujack et al., 2015).

Lunar cycle

Some patterns of animal behaviour linked to the lunar cycle can be explained because a full moon facilitates visual communication at night, can provide a time cue for synchronised events, or just scares normally night-active nocturnal animals into the shadows.

As has been reported in Iberian estuaries (Guadalquivir, Ebre and Ter), analysis of glass eel (*A. anguilla*) catches from 1927 to 1998 in the Adour estuary showed as well that, among environmental conditions, moon phase and temperature were determining factors for catch variability. These studies showed the importance of night brightness on the migratory behaviour of glass eels and consequently on the accessibility of that species to fishing (Casamayor et al., 2001).

In six highland streams in the Elbe river catchment area, the Czech Republic, lunar phase appeared to be the key factor that influenced the timing of brown trout (*S. trutta*) migration activity on a daily basis. Highest migration distance per day occurred during periods of a new moon, whereas the lowest migration distance per day occurred during the full moon. Furthermore, migration distance per day decreased with increasing river slope. The other variables tested (sex and physicochemical parameters, such as flow, pH, conductivity, and dissolved oxygen) did not affect brown trout migration activity. Furthermore, analyses revealed a significant impact of moon phase on brown trout migration that has not been previously described for this species (Slavík et al., 2012).

Large oceanic features

Other phenomena could be key for some age groups of diadromous species, like glass eel, which vary significantly from one year to another: long-term (inter-annual) changes have been positively correlated with oceanic factors related to recruitment success (NAO index and primary production at the spawning area) as well as local environmental factors (westerly and southerly wind mixing indexes and rainfall) (Arribas et al., 2012).

Salinity

This capacity differs between species, but fish have the capacity to keep their plasma osmotic concentration constant through osmoregulation. Therefore, the high osmoregulation capacity of the common goby (*P. microps*) (Rigal et al. 2008), among other species, is probably the reason for its dominance in salty Mediterranean coastal lagoons, with a higher preference for eurihaline environments. Likewise, the osmoregulation capacity of the endangered Iberian toothcarp (*A. iberus*), in whatever circumstances, also seems to be very useful for avoiding competition with the invasive eastern mosquitofish (*Gambusia holbrooki*) in more saline habitats (Doadrio, 2001; Caiola & Sostoa, 2005).

The low osmoregulation capacity of the juveniles of leaping mullet (*Liza saliens*) and golden grey mullet (*L. aurata*), together with their optimisation of growth at high salinity levels (Cardona et al., 2008), might also explain their distribution, being absent in freshwater areas and preferring high salinity areas. In Mediterranean coastal lagoons, salinity has been pointed out to be a key factor in determining the distribution pattern of mullets (Lasserre & Gallis, 1975; Cardona, 2006; Mićković et al., 2010): flathead grey mullet (*M. cephalus*) and thinlip grey mullet (*L. ramada*) prefer oligohaline and freshwater conditions; thicklip grey mullet (*C. labrosus*) and leaping mullet (*L. saliens*) show a preference for intermediate mixohaline conditions; while golden grey mullet (*L. aurata*), the least tolerant species, has an affinity for more maritime conditions. This explains why in the lower parts of Mediterranean rivers thinlip grey mullet (*L. ramada*) is clearly dominant, flathead grey mullet (*M. cephalus*) occupies the subdominant position, and thicklip grey mullet (*C. labrosus*), leaping mullet (*L. saliens*) and golden grey mullet (*L. aurata*) are rarer species, contrary to what happens in estuaries and coastal lagoons. Quite similarly to what happens in the Iberian Peninsula (Cardona, 2006) and Montenegro (Mićković et al., 2010), the seasons of the first appearance of migratory fry are between October and July.

Physiological and behavioural changes in glass eels seemed to occur gradually along the salinity gradient in the brackish zone of the Guadalquivir estuary. This change in glass eel migration behaviour may be due to individuals being at a different stage: when non-pigmented glass eels arrive at the estuary, they do not show lucifugous (light-avoiding) behaviour and so they are also caught during the day (Gandolfi et al., 1984); however, as older pigmented glass eels migrate upstream, they begin to show lucifugous behaviour and are mainly active at night (Almeida et al., 2012; Santos et al., 2014).

Water quality

When the oxygen content of the water declines, almost all species increase their ventilation frequency to cope with this deficit, but below a certain threshold most fish move to the surface of the water and exhibit so-called aquatic surface respiration. This increases predation risks. Daily variations in oxygen concentrations make hypoxic environments unfavourable for a lot of fish, at least at night, but, as is common in tropical regions, they can act as refuges for several prey species in light of the relative intolerance of most predators to low oxygen concentrations (Lucas & Baras, 2001).

5.5. Conclusions

We highlight that:

- Almost all Iberian freshwater fish clearly migrate. The great majority are potamodromous species (cyprinids, salmonids, etc.), and also include diadromous species, in an equal proportion of anadromous (European sturgeon, shads, etc.) and catadromous (European eel, mullets, etc.).

- Habitat requirements are different for each life stage (egg, larva, juvenile or adult), so individuals need to occupy and move between different habitats throughout their life.

- Only in very specific situations, it has been considered that migration may not be essential (except at metapopulation scale). It is possible that, if fish have good feeding conditions and reproduction in the area or section where they live, they will not tend to make long journeys.

- Spawning, dispersion, feeding, refuge and displacement are associated with migration behaviour.

- The principal cues or factors which influence fish migration behaviour of Iberian freshwater fish migration are: sexual maturity and condition of fish, water temperature, river flow, currents, hydrology and meteorology, diurnal/nocturnal rhythm or photoperiod, tidal cycle, large oceanic features, moonlight, turbidity, salinity and water quality. The possible relationship between electric and magnetic fields and imprinted or inherited information on a route with Iberian freshwater fish migration has not yet been assessed.

- The spawning period is considered a primary driver of freshwater Iberian fish migration. Their spawning and other migrating periods are extended, particularly long, and variable, changing between years, adapting these periods to the great year-on-year variability (i.e. of rainfall and water temperature) that is characteristic of the Mediterranean climate. Most females have multiple spawning (they can spawn several times each year). It is an advantage in the highly unpredictable hydrological regime of Mediterranean environments. At lower latitudes, spawning and other migrating periods are earlier, and later for autumn and winter spawners and migrators.

- Migratory movements for most fish are important in and out of the spawning period, all year round, except in the coldest months and only for few species, for feeding and refuge.

- Fish migrating rates of both potamodromous and diadromous are very high in spring (cyprinids, European sturgeon, shads, mullets, etc.), associated with the prevailing spawning period in the area, but also following high or moderate peak flows or water level changes, and increasing water temperature. Other groups (salmonids, eel, etc.) especially migrate between autumn and spring. Their arrival at specific areas permits to exploit the temporary habitat availability and waves of production (upstream) of the river or coastal lagoon systems in order to optimise the reproductive process (fry and juveniles) or, simply, to feed in these more productive and less salty environments than the sea.

- Combining the various species present in each river, migrating movements cover all or practically all year round. Therefore, coinciding with other countries such as the United Kingdom (Armstrong et al., 2010) and France (Porcher & Travade, 2002; Baudoin et al., 2014), unrestricted movement is almost a permanent requirement: Iberian and Mediterranean rivers, lakes and coastal lagoons should always be connected, without transverse obstacles, or fish passes should always be in operation.
- However, we need to improve knowledge on migrating behaviour of several native Iberian freshwater fish species with and without socio-economic interest, in relation to most barriers and fish passes, and especially downstream migration of all fish species.

Table 5. Spawning and migrating periods of Iberian native freshwater fish species. R= reproductive adults, Y=young, F=fry, ·=few individuals,?=probably.

Reference	Basin / *region*	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
		Syngnathidae																																				
Sostoa et al., 1990	Ebre	*Syngnathus abaster*														?	?	?																				
López et al., 2015	Ebre	*Syngnathus abaster*																																				
Doadrio, 2001	*Spain*	*Syngnathus abaster*																																				
		Petromyzontidae																																				
Mateus et al., 2013	Esmoriz	*Lampetra alavariensis*				?	?									?	?																					
Mateus et al., 2013	Tejo	*Lampetra auremensis*				?	?									?	?																					
Ferreira, 2011	Tejo	*Lampetra fluviatilis*																																				
Mateus et al., 2013	Sado	*Lampetra lusitanica*				?	?									?	?																					
Ferreira, 2011	*Portugal*	*Lampetra planeri*																																				
Salvador, 2003	*Portugal*	*Lampetra planeri*																																				
Doadrio et al., 2011	Adour	*Lampetra planeri*		·			·	·																														
Queral et al., 1999	Ebre	*Petromyzon marinus*																																				
Silva et al., 2013	Ulla	*Petromyzon marinus*																									Y	Y	Y	Y	Y	·			·	Y	Y	Y
Silva, 2014	Miño	*Petromyzon marinus*																									Y	Y	Y	Y	Y					Y	Y	Y
Doadrio et al., 2011	*Spain*	*Petromyzon marinus*																																				
Almeida et al., 2000	Mondego	*Petromyzon marinus*													·											·												
Santos et al., 2004	Lima	*Petromyzon marinus*													·				·																			
Santos et al., 2014	Lima	*Petromyzon marinus*																		·																		
		Cottidae																																				
Doadrio et al., 2011	Garona	*Cottus hispaniolensis*																																				
Sousa-S. et al., 2014a	Bidasoa	*Cottus aturi*			?	?	?	?																														
		Acipenseridae																																				
Porres & Farnós, 1999	Ebre	*Acipenser sturio*													·	·					·	Y	Y															
Classen, 1944	Guadalquivir	*Acipenser sturio*																																				

Table 5 bis. Spawning and migrating periods of Iberian native freshwater fish species. R= reproductive adults, Y=young, F=fry, ·=few individuals,?=probably.

Reference	Basin / region	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
Clupeidae																																						
Sostoa et al., 1990	Ebre	*Alosa alosa*																														R						
Doadrio et al., 2011	Ebre	*Alosa alosa*																														R						
Nachón et al., 2015	Minho and Ulla	*Alosa alosa*														*																R	R	R				
Mota et al., 2015	Minho	*Alosa alosa*													*	*					*						Y								Y	Y	Y	Y
Pombo & Re., 2002	Aveiro	*Alosa alosa*																																				
Sostoa et al., 1990	Ebre	*Alosa fallax*																														R						
López et al., 2007	Ebre	*Alosa fallax*																																				
López et al., 2015	Ebre	*Alosa fallax*														*	*															Y	Y	Y	Y	Y		
As. Pesca Resp.	Ebre	*Alosa fallax*																																				
Doadrio et al., 2011	*Spain*	*Alosa fallax*																														R						
Nachón et al., 2015	Minho and Ulla	*Alosa fallax*															*															R	R	R				
Anguillidae																																						
CERM database	Ribera de Llançà	*Anguilla anguilla*																																	R	R		
Ordeix et al., 2011	Tordera	*Anguilla anguilla*																F																				
Aparicio et al., 2012	Ebre	*Anguilla anguilla*																		Y	Y	Y																
Demestre et al., 1977	Ebre	*Anguilla anguilla*																					*	F	F	F												
Gisbert & López, 2008	Ebre	*Anguilla anguilla*													F	F	F								F	F												
Gómez, 2014	Ebre	*Anguilla anguilla*													F	F	F							F	F	F												
Lobón. et al., 1995	Esva	*Anguilla anguilla*													F	F	F							F	F	F	R	R	R						R	R	R	R
Lara, 1994	Nalón	*Anguilla anguilla*													F	F	*	*						*	*	F												
Arribas et al, 2012	Guadalquivir	*Anguilla anguilla*													F	F	F	F	F	*	*	*	*	F	F	F												
Drake & Arias, 1991	Esteros Cádiz	*Anguilla anguilla*													F	F	*	F	F	F				*	F	F												
Doadrio, 2001	*Spain*	*Anguilla anguilla*													F	F	F	F	*	*	*	*	*	F	F	F												
Cobo et al., 2014	Ulla	*Anguilla anguilla*																									R/*	*/*	*/*	*/*	*/*	*/Y	*/Y	R/Y	R/*	R/*	R/*	R/*
Antunes & W., 1996	Miño	*Anguilla anguilla*													*	F	F	*						*	*	*												
Domingos, 1992	Mondego	*Anguilla anguilla*													F	*	F	*	*					*	F	*												
Santos et al., 2002	Lima	*Anguilla anguilla*																	*			*	*	*														
Santos et al., 2004	Lima	*Anguilla anguilla*																*				*		*														
Santos et al., 2014	Lima	*Anguilla anguilla*													*	*																						

Reference	Basin / *region*	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
		Atherinidae																																				
Sostoa et al., 1990	Ebre	*Atherina boyeri*																																				
López et al., 2015	Ebre	*Atherina boyeri*																	Y	Y																		
Jiménez et al., 2002	*Valencia region*	*Atherina boyeri*																																				
Fernán.-D. et al., 1988	Guadalquivir	*Atherina boyeri*	*	*																																		
Doadrio et al., 2011	Guadalquivir	*Atherina boyeri*																																				
		Salmonidae																																				
Utrilla & Lobón, 1999	Esva	*Salmo salar*																												R	Y							
Caballero, 2013	Ulla	*Salmo salar*														*											R	R	R	R								R
Doadrio et al., 2011	*Spain*	*Salmo salar*																																				
Santos et al., 2002	Lima	*Salmo salar*														*																						
Santos et al., 2014	Lima	*Salmo salar*																					*															
Ordeix et al., 2011	Ter	*Salmo trutta*																*																				
Ordeix et al., 2011	Ter	*Salmo trutta*																																				
Ordeix et al., 2011	Ebre	*Salmo trutta*																																				
Ordeix et al., 2011	Ebre	*Salmo trutta*																																				
Sostoa et al., 1990	*Catalonia*	*Salmo trutta*																																				
Rocaspana et al., 2012	Ebre	*Salmo trutta*																																				
Yécora et al., 2013	Oria	*Salmo trutta*																																				
García & Braña, 1988	Aller	*Salmo trutta*																																				
Lobón-Cer.et al., 1986	Duero	*Salmo trutta*																																				
Mayo et al., 1995	Tajo	*Salmo trutta*																																				
Gortázar et al., 2007	Guadalquivir	*Salmo trutta*																																				
Larios-Lóp. et al., 2015	Guadal. & Segura	*Salmo trutta*																																				
Santos et al., 2002	Lima	*Salmo trutta*															*	*				*	*			*												
Santos et al., 2004	Lima	*Salmo trutta*													*					*	*	*			*	*												
Santos et al., 2014	Lima	*Salmo trutta*															*				*	*																
Toledo et al., 1993	Narcea and Cares	*Salmo trutta (trutta)*																																				
Caballero, 2013	Ulla	*Salmo trutta (trutta)*														*											R	R	R/Y	R/Y	R/Y							R

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Reference	Basin / region	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
		Cyprinidae																																				
Sostoa et al., 1990	*Catalonia*	*Achondrostoma arcasii*				x	x																															
Jiménez et al., 2002	*Valencia region*	*Achondrostoma arcasii*					x	x																														
Doadrio et al., 2011	*Spain*	*Achondrostoma arcasii*					x	x																														
Santos et al., 2002	Lima	*Achondrostoma arcasii*													*	*		*	x	x	x	x	*	*	*													
Santos et al., 2004	Lima	*Achondrostoma arcasii*															*		*		*	*	*															
Robalo et al., 2008	Safarujo	*Achondroma occidentale*				x	x																															
Santos et al., 2014	Lima	*Achondrostoma oligolepis*													*	*		*	x	x	x	x	*	*	*													
Doadrio & Elvira, 2007	Duero	*Achondrostoma salmantinum*				?	?	?																														
Salvador, 2009	Guadiana	*Anaecypris hispanica*				x	x									?	?									?												
Doadrio et al., 2011	Guadiana	*Anaecypris hispanica*				x																																
Aparicio & Sostoa, 1999	Llobregat	*Barbus haasi*				x	x	x	x																							R						
Casals, 2005	Llobregat	*Barbus haasi*						x	x																													
CERM database	Llobregat	*Barbus haasi*																						x														
Ordeix et al., 2011	Ebre	*Barbus haasi*																x			x																	
Casals, 2005	Ebre	*Barbus haasi*			x	x	x	x	x	x																												
Sostoa et al., 1990	*Catalonia*	*Barbus haasi*				x	x	x																														
Verdiell, 2006	Ebre and Túria	*Barbus haasi*			x	x	x	x	x	x																												
Doadrio et al., 2011	*Spain*	*Barbus haasi*				x	x	x																														
Casals, 2005	La Muga	*Barbus meridionalis*		x	x	x	x	x	x																													
Ordeix, 2015	Fluvià	*Barbus meridionalis*					x	x	x									x	x	x	x			x	x													
Ordeix et al., 2011	Ter	*Barbus meridionalis*							x												x			x														
CERM database	Ter	*Barbus meridionalis*				x	x										x	x	x																			
Ordeix et al., 2011	Ter	*Barbus meridionalis*				x	x	x	x									*	x	x	x	x	x	*	*													
Ordeix et al., 2011	Tordera	*Barbus meridionalis*																x	x																			
Sostoa et al., 1990	*Catalonia*	*Barbus meridionalis*					x	x																														
Zamora, 2011	*Catalonia*	*Barbus meridionalis*		x	x	x	x	x	x																													
Doadrio et al., 2011	*Catalonia*	*Barbus meridionalis*					x	x																														

Reference	Basin / region	Species
Ordeix et al., 2011	Ebre	*Gobio lozanoi*
Aparicio et al., 2012	Ebre	*Gobio lozanoi*
Amat-Trigo, 2015	Bidasoa	*Gobio lozanoi*
Doadrio et al., 2011	*Spain*	*Gobio lozanoi*
Robalo et al., 2013	Mira & Bensafrim	*Iberochondrostoma almacai*
Ferná.-D. & H., 1995	Guadiana	*Iberochondrostoma lemmingii*
Doadrio et al., 2011	*Spain*	*Iberochondrostoma lemmingii*
Robalo et al., 2009	Tejo and Sado	*Iberochondrostoma lusitanicum*
Sousa-S. et al., 2014d	Tejo	*Iberochondrostoma olisiponensis*
Doadrio et al., 2011	Guadalquivir	*Iberochondrostoma oretanum*
Sanz et al., 2013	Duero	*Luciobarbus bocagei*
Lobó.-C. & F.-D., 1984	Tajo	*Luciobarbus bocagei*
Salvador, 2012a	Duero and Tajo	*Luciobarbus bocagei*
Doadrio et al., 2011	Tajo	*Luciobarbus bocagei*
Santos et al., 2002	Lima	*Luciobarbus bocagei*
Santos et al., 2004	Lima	*Luciobarbus bocagei*
Santos et al., 2014	Lima	*Luciobarbus bocagei*
Santos et al., 2014	Lima	*Luciobarbus bocagei*
Morán, 2014	Tajo & Guadia.	*Luciobarbus comizo*
Doadrio et al., 2011	Tajo & Guadia.	*Luciobarbus comizo*
Ordeix et al., 2011	Ebre	*Luciobarbus graellsii*
Sostoa et al., 1990	Ebre	*Luciobarbus graellsii*
Aparicio et al., 2012	Ebre	*Luciobarbus graellsii*
Casals, 2005	Ebre	*Luciobarbus graellsii*
Casals, 2005	Ebre	*Luciobarbus graellsii*
Salvador, 2013	Ebre	*Luciobarbus graellsii*
Doadrio et al., 2011	Ebre	*Luciobarbus graellsii*
Jiménez et al., 2002	Júcar	*Luciobarbus guiraonis*
Doadrio et al., 2011	*Spain*	*Luciobarbus guiraonis*

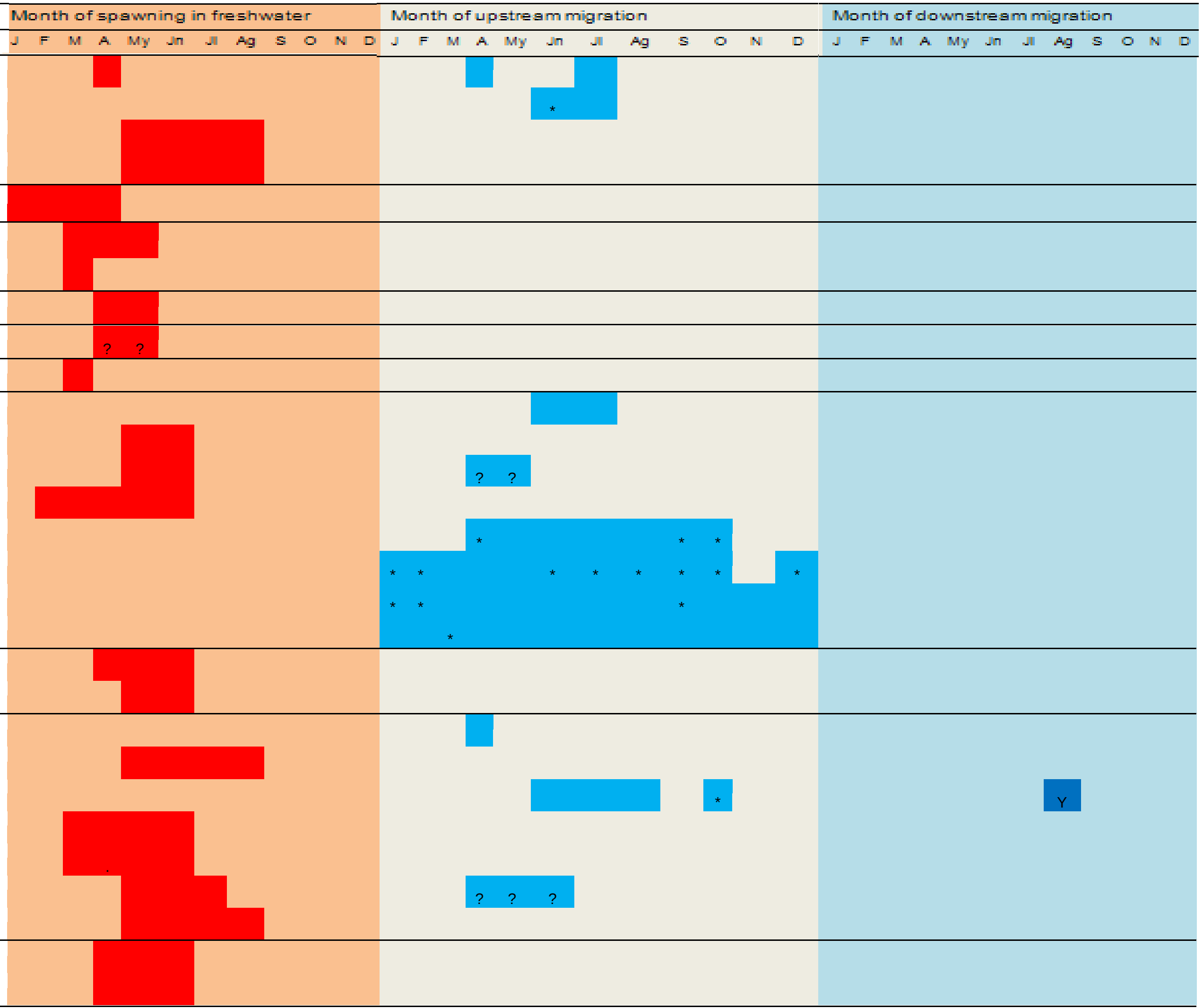


Table 5 bis. Spawning and migrating periods of Iberian native freshwater fish species. R= reproductive adults, Y=young, F=fry, ·=few individuals,?=probably.

Reference	Basin / region	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
Morán, 2010	Guadiana	*Luciobarbus microcephalus*															?	?	?																			
Doadrio et al., 2011	Guadiana	*Luciobarbus microcephalus*																																				
Her. & Ferná.-D., 1992	Guadalquivir	*Luciobarbus sclateri*																																				
Andreu-Soler, 2006	*S Spain*	*Luciobarbus sclateri*																?	?																			
Encina et al., 2006	Guadalete	*Luciobarbus sclateri*																																				
Doadrio et al., 2011	Guadalquivir	*Luciobarbus sclateri*																																				
Jiménez et al., 2002	Júcar	*Parachondrostoma arrigonis*																																				
Elvira & Almodó., 2008	Júcar	*Parachondrostoma arrigonis*																																				
Ordeix et al., 2011	Ebre	*Parachondrostoma miegii*																																				
Sostoa et al., 1990	Ebre	*Parachondrostoma miegii*																																				
Casals, 2005	Ebre	*Parachondrostoma miegii*																																				
Jiménez et al., 2002	Berga. & Sénia	*Parachondrostoma miegii*																																				
Jiménez et al., 2002	*Valencia region*	*Parachondrostoma turiense*																																				
Doadrio et al., 2011	Túria and Millars	*Parachondrostoma turiense*																																				
Ordeix et al., 2011	Ebre	*Phoxinus bigerri*																																				
Leunda et al., 2010	*Spain*	*Phoxinus bigerri*							*																													
Doadrio et al., 2011	*Spain*	*Phoxinus bigerri*																																				
Sanz et al., 2013	Duero	*Pseudochondrostoma duriense*																																				
Doadrio et al., 2011	Duero and Miño	*Pseudochondrostoma duriense*																																				
Santos et al., 2014	Lima	*Pseudochondrostoma duriense*													*	*							*	*														
Santos et al., 2014	Lima	*Pseudochondrostoma duriense*															*	*	*	*						*												
Santos et al., 2014	Lima	*Pseudochondrostoma duriense*														*	*	*	*	*						*												
Her. & Fern.-D., 1994	Guadalquivir	*Pseudochondrostoma polylepis*																																				
Doadrio et al., 2011	Tajo	*Pseudochondrostoma polylepis*																																				
Santos et al., 2002	Lima	*Pseudochondrostoma polylepis*													*	*							*															
Santos et al., 2004	Lima	*Pseudochondrostoma polylepis*													*	*				*	*	*	*	*	*	*												
Encina et al., 2006	Guadalete	*Pseudochondrostoma willkommii*																																				
Doadrio et al., 2011	Guadi. & Guada.	*Pseudochondrostoma willkommii*																																				
Fernán.-D. & H., 1994	Guadalquivir	*Squalius alburnoides*																																				
Ribeiro et al., 2003	Guadiana	*Squalius alburnoides*																																				

Reference	Basin / region	Species	Month of spawning in freshwater (J F M A My Jn Jl Ag S O N D)	Month of upstream migration (J F M A My Jn Jl Ag S O N D)	Month of downstream migration (J F M A My Jn Jl Ag S O N D)
Sousa-Sa. et al., 2009	Arade & Bordeira	*Squalius aradensis*	? ? ? ?		
Doadrio et al., 2011	*Spain*	*Squalius carolitertii*			
Santos et al., 2002	Lima	*Squalius carolitertii*		* * * *	
Santos et al., 2004	Lima	*Squalius carolitertii*		* * * * * * * *	
Doadrio et al., 2011	Tajo	*Squalius castellanus*			
Ordeix, 2015	Fluvià	*Squalius laietanus*			
CERM database	Ter	*Squalius laietanus*			
Ordeix et al., 2011	Ter	*Squalius laietanus*			
Ordeix et al., 2011	Tordera	*Squalius laietanus*			
Casals, 2005	Llobregat	*Squalius laietanus*			
Ordeix et al., 2011	Ebre	*Squalius laietanus*			
Casals, 2005	Ebre	*Squalius laietanus*			
Casals, 2005	Ebre	*Squalius laietanus*			
Sostoa et al., 1990	*Catalonia*	*Squalius laietanus*			
Sousa-S. et al., 2014b	Guada. & Guadi.	*Squalius malacitanus*	? ? ? ?		
Doadrio et al., 2011	Guadalquivir	*Squalius palaciosi*			
Ferná.-D. & H., 1995a	Guadalquivir	*Squalius pyrenaicus*			
Doadrio et al., 2011	Spain	*Squalius pyrenaicus*			
Magalhães et al., 2003	Mira	*Squalius torgalensis*			
Jiménez et al., 2002	Júcar	*Squalius valentinus*			
		Cobitidae			
Perdices, 2013	*N Spain*	*Cobitis calderoni*			
Doadrio et al., 2011	*Spain*	*Cobitis calderoni*			
Sostoa et al., 1990	*Catalonia*	*Cobitis paludica*			
Jiménez et al., 2002	*Valencia region*	*Cobitis paludica*			
Lobón-Cer. & Z., 1984	Duero	*Cobitis paludica*			
Soriguer et al., 2000	Guadalquivir	*Cobitis paludica*			
Oliva-Pate. et al., 2002	Guadalquivir	*Cobitis paludica*			
Sánchez-Carmo., 2013	*Spain*	*Cobitis paludica*			
Doadrio et al., 2011	*Spain*	*Cobitis paludica*			
Sousa-S. et al., 2014c	Duero and Tajo	*Cobitis vettonica*			

Table 5 bis. Spawning and migrating periods of Iberian native freshwater fish species. R= reproductive adults, Y=young, F=fry, ·=few individuals,?=probably.

Reference	Basin / region	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
		Homalopteridae																																				
Ordeix et al., 2011	Ebre	*Barbatula quignardi*																																				
Sostoa et al., 1990	Ebre	*Barbatula quignardi*																																				
Doadrio et al., 2011	*Spain*	*Barbatula quignardi*																																				
		Gasterosteidae																																				
Sostoa et al., 1990	*Catalonia*	*Gasterosteus aculeatus*																																				
López et al., 2015	Ebre	*Gasterosteus aculeatus*															?	?																				
Jiménez et al., 2002	*Valencia region*	*Gasterosteus aculeatus*																																				
Fernández et al., 2015	*Spain*	*Gasterosteus aculeatus*																																				
Doadrio et al., 2011	*Spain*	*Gasterosteus aculeatus*																																				
		Cyprinodontidae																																				
Clavero et al., 2004	Río de la Vega	*Aphanius baeticus*																																				
Fernán.-D. et al., 1998	Guadalquivir	*Aphanius baeticus*																																				
Doadrio et al., 2011	*Andalucía region*	*Aphanius baeticus*																																				
Sostoa et al., 1990	Ebre	*Aphanius iberus*																																				
López et al., 2015	Ebre	*Aphanius iberus*																																				
Garc.-B. & M.-A., 1993	Muga	*Aphanius iberus*																																				
Vargas & Sostoa, 1997	Ebre	*Aphanius iberus*																																				
Jiménez et al., 2002	*Valencia region*	*Aphanius iberus*																																				
Oliva-Pate. et al., 2008	Marchamalo	*Aphanius iberus*																																				
		Valenciidae																																				
Sostoa et al., 1990	Ebre	*Valencia hispanica*																																				
López et al., 2015	Ebre	*Valencia hispanica*																																				
Caiola, 2011	Ebre & Pego-O.	*Valencia hispanica*																																				
Jiménez et al., 2002	*Valencia region*	*Valencia hispanica*																																				

Reference	Basin / region	Species	Month of spawning in freshwater (J F M A My Jn Jl Ag S O N D)	Month of upstream migration (J F M A My Jn Jl Ag S O N D)	Month of downstream migration (J F M A My Jn Jl Ag S O N D)
Blenniidae					
Vila-G.& Mor.-A., 1998	Ter	*Salaria fluviatilis*			
Sostoa et al., 1990	Ebre	*Salaria fluviatilis*			
Vinyoles, 1993	Ebre	*Salaria fluviatilis*			
Aparicio et al., 2012	Ebre	*Salaria fluviatilis*		* * * *	*
López et al., 2015	Ebre	*Salaria fluviatilis*	*		
Jiménez et al., 2002	Júcar	*Salaria fluviatilis*			
Rodríguez-Jimé., 2001	Guadiana	*Salaria fluviatilis*			
Salvador, 2012b	*Spain*	*Salaria fluviatilis*			
Doadrio et al., 2011	*Spain*	*Salaria fluviatilis*			
Gobiidae					
Sostoa et al., 1990	Ebre	*Pomatoschistus microps*	? ? ? ?		
López et al., 2015	Ebre	*Pomatoschistus microps*			
Fernán.-D. et al., 2000	Guadalquivir	*Pomatoschisyus microps*			
Doadrio et al., 2011	*Spain*	*Pomatoschistus microps*			
Mugilidae					
Sostoa et al., 1990	Ebre	*Chelon labrosus*			
López et al., 2015	Ebre	*Chelon labrosus*		Y Y Y Y Y Y Y Y	R R R
Fernán.-D. et al., 2000	Guadalquivir	*Chelon labrosus*			
Doadrio et al., 2011	*Spain*	*Chelon labrosus*			
Ordeix et al., 2011	Ter	*Mugil cephalus*		* * *	
Sostoa et al., 1990	Ebre	*Mugil cephalus*			
López et al., 2015	Ebre	*Mugil cephalus*		Y Y	
Fernán.-D. et al., 2000	Guadalquivir	*Mugil cephalus*		Y/R Y/R	
Santos et al., 2004	Lima	*Mugil cephalus*		* * * *	
Ordeix et al., 2011	Ter	*Liza ramada*		* * *	
Sostoa et al., 1990	Ebre	*Liza ramada*			
López et al., 2015	Ebre	*Liza ramada*			? ?
Aparicio et al., 2012	Ebre	*Liza ramada*		* Y/R Y/R Y/R	R
Fernán.-D. et al., 2000	Guadalquivir	*Liza ramada*		R R Y/R Y/R	
Almeida, 1996a	*Portugal*	*Liza ramada*			

Table 5 bis. Spawning and migrating periods of Iberian native freshwater fish species. R= reproductive adults, Y=young, F=fry, ·=few individuals,?=probably.

Reference	Basin / *region*	Species	Month of spawning in freshwater												Month of upstream migration												Month of downstream migration											
			J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D	J	F	M	A	My	Jn	Jl	Ag	S	O	N	D
Sostoa et al., 1990	Ebre	*Liza saliens*																																				
López et al., 2015	Ebre	*Liza saliens*													Y						Y	Y	Y	Y	Y	Y												
Fernán.-D. et al., 2000	Guadalquivir	*Liza saliens*																		R	R	Y/R				Y				R	R	R						
López et al., 2015	Ebre	*Liza aurata*													Y	Y	Y	Y	Y	Y				Y	Y	Y												
Fernán.-D. et al., 2000	Guadalquivir	*Liza aurata*																					?	?	?													
Pombo & Rebe., 2002	Aveiro	*Liza aurata*																											R									
Almeida, 1996a	*Portugal*	*Liza aurata*																																				
Pleuronectidae																																						
Sostoa et al., 1990	Ebre	*Platichthys flesus*																?	?																			
Doadrio et al., 2011	*Spain*	*Platichthys flesus*																				?																
Freitas et al., 2009	Minho	*Platichthys flesus*																																				
Martinho et al., 2008	Mondego	*Platichthys flesus*																										Y	Y									
Moronidae																																						
Sostoa et al., 1990	Ebre	*Dicentrarchus labrax*																																				
López et al., 2015	Ebre	*Dicentrarchus labrax*																		Y	Y	Y																
Fernán.-D. et al., 2000	Guadalquivir	*Dicentrarchus labrax*																		*	*	*	*	*	*													
Martinho et al., 2008	Mondego	*Dicentrarchus labrax*																																Y				

6. Fish pass assessments in Catalonia

6.1. Introduction

Between 2005 and 2010, river connectivity and fish passes in Catalan rivers were assessed in order to improve design, construction, management and assessment of fish passes according to international best practices (Marmulla & Welcomme, 2002; Armstrong et al., 2004). This study started in 2005 under an agreement between the Catalan Water Agency (ACA, Agència Catalana de l'Aigua) and the Center for the Study of Mediterranean Rivers - Ter River Museum (CERM, Centre d'Estudis dels Rius Mediterranis - Museu del Ter), in order to follow the requirements of the European Water Framework Directive (2000/60/EC; EC, 2000) and the Environmental Flows Plan for Catalonia (7/2006). Between 2005 and 2010, this work was funded by ACA. Additional support was provided by the Interreg IIIC "Community Rivers" Project (2004-2007), the "Obra social" (social welfare) of UNNIM savings bank (2012) and the funds for conservation of the Spanish Fundación Biodiversidad ("Riberes del Ter" Project, 2013).

This assessment was carried out in two phases:

(1) Between 2005 and 2006, a preliminary assessment of fish passes in Catalonia was carried out through direct inspection of 78 fishways (Ordeix et al., 2011). Between 2007 and 2010, this was updated after visits to 16 newly built fish passes. In 2010, a database of 95 obstacles and their associated fishways was compiled, including their ICF index (Solà *et al.*, 2011) calculation.

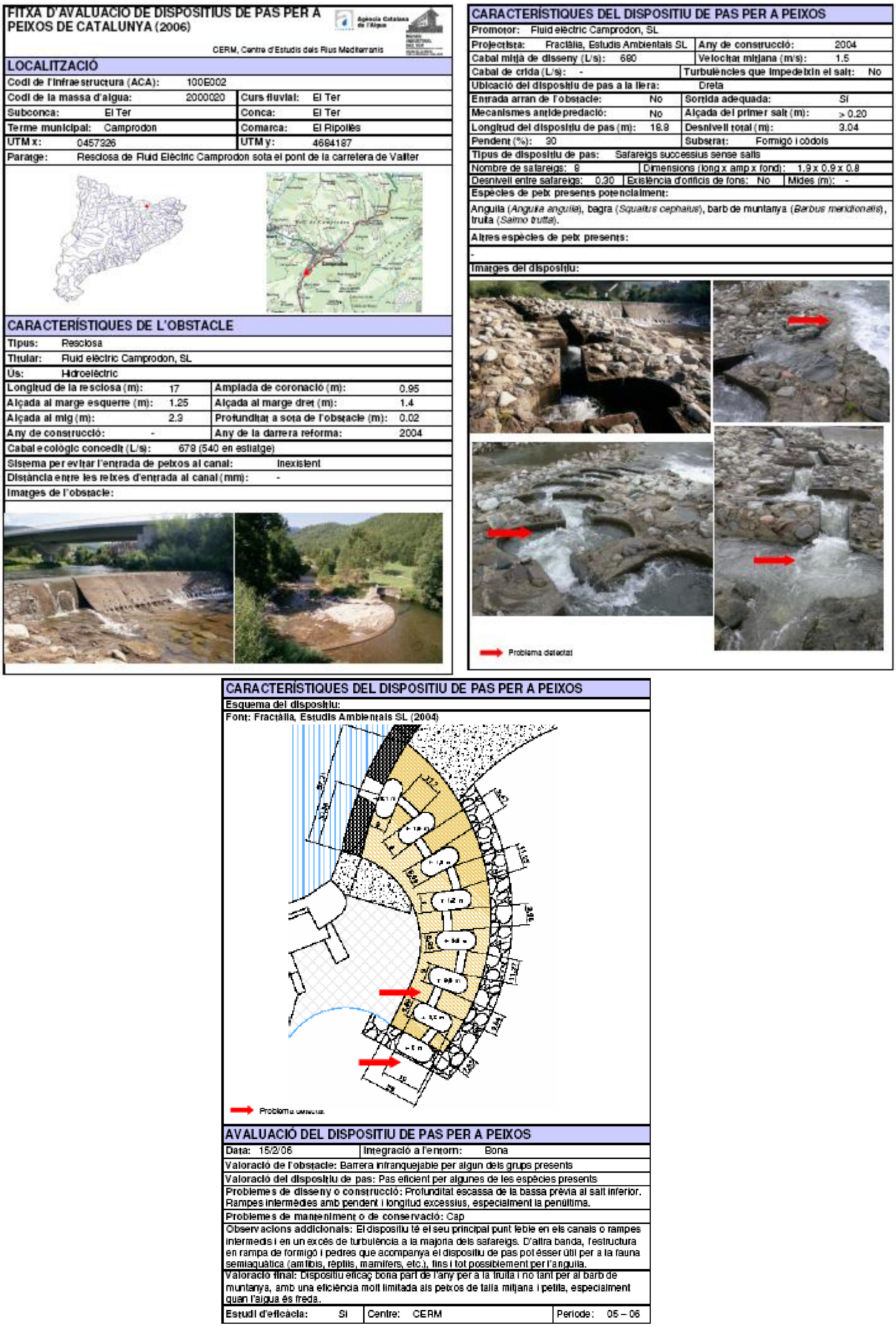
(2) During the period 2006 to 2012, an analysis of the effectiveness of 10 representative fish passes was carried out (partially published in Ordeix et al., 2011), for a range of different types of river stretches, fish species and fish passes. These (5, 2, 2 and 1, in the Ter, Ebre, Llobregat and Tordera river basins, respectively) were located at weirs associated with hydropower plants (5), gauging stations (4) and irrigation (1).

6.2. Methods

Several methodologies were used to check fish pass effectiveness, and this was complemented by collection of environmental data:

1. **General data collection**, in order to collect general information on all existing fish passes in Catalonia, to fill a database (see Fig. 12), including ICF index (Solà et al., 2011) calculation.
2. **Indirect estimation techniques**: using electrofishing or trapping systems in the 10 selected fish passes, group mark-recapture methods (injecting an acrylic paint in the caudal fin of the fish) in one case, and individual mark-recapture methods (inserting PIT tags in the peritoneal cavity of fishes) in one other case.
3. **Direct estimation techniques**: involved the installation of fish traps upstream of the facility (at the water intake upstream of the fish pass) in the 10 selected fish passes, and complementary visual counts in one case. In all 10 selected cases, a permanent mesh of 0.01 x 0.01 m was installed at a distance between 2 and 5 m upstream of the fish trap, as a deflector in order to prevent clogging of the trap network by spam (leaves and small branches).

Deviations in the most abundant fish species size frequencies downstream and upstream of the obstacle, or downstream and crossing the water intake upstream of the fish passes, were analysed by means of a Chi-square test using the statistical package SPSS (for Windows, version 15.0, SPSS Inc., Chicago, Illinois).



FITXA D'AVALUACIÓ DE DISPOSITIUS DE PAS PER A PEIXOS DE CATALUNYA (2006)

Agència Catalana de l'Aigua

CERM, Centre d'Estudis dels Rius Mediterranis

LOCALITZACIÓ

Codi de l'infraestructura (ACA):	100E002		
Codi de la massa d'aigua:	2000020	Curs fluvial:	El Ter
Subconca:	El Ter	Conca:	El Ter
Terme municipal:	Camprodon	Comarca:	El Ripollès
UTM x:	0457326	UTM y:	4684187
Paratge:	Resclosa de Fluid Elèctric Camprodon sota el pont de la carretera de Vallter		

CARACTERÍSTIQUES DE L'OBSTACLE

Tipus:	Resclosa		
Titular:	Fluid elèctric Camprodon, SL		
Ús:	Hidroelèctric		
Longitud de la resclosa (m):	17	Amplada de coronació (m):	0.95
Alçada al marge esquerre (m):	1.25	Alçada al marge dret (m):	1.4
Alçada al mig (m):	2.3	Profunditat a sota de l'obstacle (m):	0.02
Any de construcció:	-	Any de la darrera reforma:	2004
Cabal ecològic concedit (L/s):	679 (540 en estiatge)		
Sistema per evitar l'entrada de peixos al canal:	Inexistent		
Distància entre les reixes d'entrada al canal (mm):	-		

Imatges de l'obstacle:

CARACTERÍSTIQUES DEL DISPOSITIU DE PAS PER A PEIXOS

Promotor:	Fluid elèctric Camprodon, SL		
Projectista:	Fractàlia, Estudis Ambientals SL	Any de construcció:	2004
Cabal mitjà de disseny (L/s):	680	Velocitat mitjana (m/s):	1.5
Cabal de crida (L/s):	-	Turbulències que impedeixin el salt:	No
Ubicació del dispositiu de pas a la llera:	Dreta		
Entrada arran de l'obstacle:	No	Sortida adequada:	Sí
Mecanismes antidepredació:	No	Alçada del primer salt (m):	> 0.20
Longitud del dispositiu de pas (m):	18.9	Desnivell total (m):	3.04
Pendent (%):	30	Substrat:	Formigó i còdols
Tipus de dispositiu de pas:	Safareigs successius sense salts		
Nombre de safareigs:	8	Dimensions (long x amp x fond):	1.9 x 0.9 x 0.8
Desnivell entre safareigs: 0.30	Existència d'orificis de fons: No	Mides (m): -	

Espècies de peix presents potencialment:

Anguila (*Anguilla anguilla*), bagra (*Squalius cephalus*), barb de muntanya (*Barbus meridionalis*), truita (*Salmo trutta*).

Altres espècies de peix presents:

-

Imatges del dispositiu:

Problema detectat

CARACTERÍSTIQUES DEL DISPOSITIU DE PAS PER A PEIXOS

Esquema del dispositiu:

Font: Fractàlia, Estudis Ambientals SL (2004)

Problema detectat

AVALUACIÓ DEL DISPOSITIU DE PAS PER A PEIXOS

Data: 15/2/06	Integració a l'entorn: Bona

Valoració de l'obstacle: Barrera infranquejable per algun dels grups presents

Valoració del dispositiu de pas: Pas eficient per algunes de les espècies presents

Problemes de disseny o construcció: Profunditat escassa de la bassa prèvia al salt inferior. Rampes intermèdies amb pendent i longitud excessius, especialment la penúltima.

Problemes de manteniment o de conservació: Cap

Observacions addicionals: El dispositiu té el seu principal punt feble en els canals o rampes intermedis i en un excés de turbulència a la majoria dels safareigs. D'altra banda, l'estructura en rampa de formigó i pedres que acompanya el dispositiu de pas pot ésser útil per a la fauna semiaquàtica (amfibis, rèptils, mamífers, etc.), fins i tot possiblement per l'anguila.

Valoració final: Dispositiu eficaç bona part de l'any per a la truita i no tant per al barb de muntanya, amb una eficiència molt limitada als peixos de talla mitjana i petita, especialment quan l'aigua és freda.

Estudi d'eficàcia: Sí	Centre: CERM	Període: 05 – 06

Figure 12. Example of an assessment sheet of the fish pass database for Catalonia: the case of Les Rocasses weir, managed by Fluid Elèctric Camprodon hydropower company, at Camprodon (Ter river, El Ripollès region). From: Ordeix et al., 2006.

6.3. Results

River obstacles

There are few pristine rivers, lakes and wetlands in Europe. Dams and weirs have changed their natural habitats, especially the characteristics of fish spawning and feeding areas, and their accessibility. Most freshwater fish populations in the Iberian Peninsula (SW Europe), including Catalonia, are also affected by various types of obstacles: dams, weirs, canals, gauging stations, hydroelectric turbines and irrigation pumps, among others, and also hydrological constraints (lack of water or natural regimes) or poor water quality (pollution) (see Fig. 13-14).

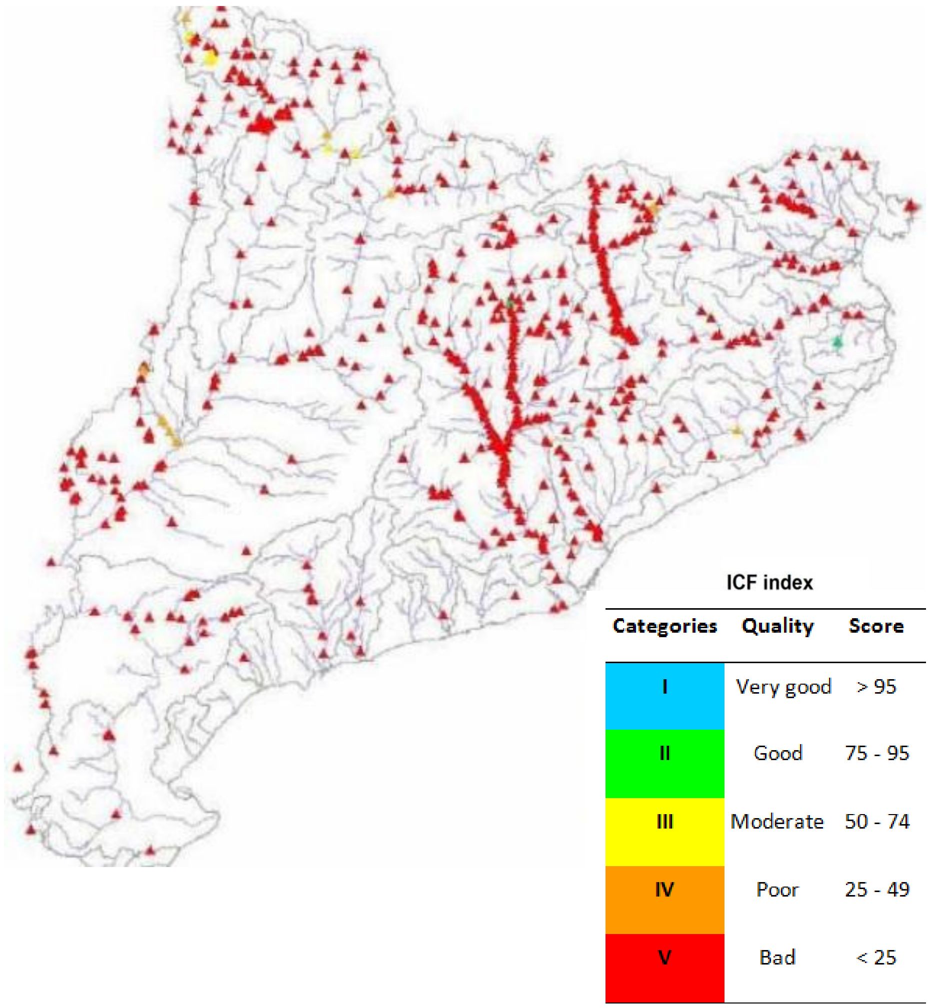


Figure 13. Map of the main river obstacles for fish in Catalonia, including the colours of the corresponding categories of the ICF index (Solà et al., 2011) for each.

Big dams

Weirs and gauging stations

Channels, hydropower and pumping stations

Culverts and low slope weirs

Low flows and pollution

Figure 14. Some types of river obstacles for fish in Catalonia.

The Catalan Water Agency located 886 large obstacles in 2010 (according to its database), mostly small weirs and some dams, which seriously affect fish migration in Catalan rivers (see Table 6):

- 740 weirs (under 15 m),
- 45 large dams (over 15 m in height), and
- 93 gauging stations.

Large river obstacles were found everywhere, but the Llobregat river basin (with 228 identified infrastructures), the Ter (165) and the Besòs (150) account for two-thirds (66%) of the total. Apart from a large number of crossings, bed sills and road and railway bridge pillars, only 95 fish passes were found among all of these river obstacles until 2010.

Dams and weirs are related to the need for a source of primary energy, which in past centuries gave rise to large textile and metallurgical industries in Catalonia along the banks of the Ter and Llobregat rivers. Hydropower was associated with human rural migration and population growth, and rivers became part of the industrial framework of the country. However, weirs and dams produced significant declines in river flow, especially in summer, with alterations of the hydrological regime, natural sediment flow (of rolling stones, gravel and sand) and ecological connectivity (longitudinal and tranverse) for fauna, especially fish.

Table 6. Big river obstacles (weirs (under 15 m), large dams (over 15 m in height) and gauging stations) in Catalonia in 2010, by river basin and in total. From: Catalan Water Agency database.

River obstacles / River basins	Muga	Fluvià	Ter	Daró	Tordera	Besòs	Llobregat	Foix	Gaià	Francolí	Coastal streams
Dams	1	0	3	0	0	3	6	2	1	0	1
Weirs	36	50	151	1	9	139	192	1	18	1	7
Gauging stations	6	3	11	0	6	8	30	1	4	4	3
Total	**43**	**53**	**165**	**1**	**15**	**150**	**228**	**4**	**23**	**5**	**11**

River obstacles / River basins	Garona	Segre	Noguera Pallaresa	Noguera Ribagorçana	Baix Ebre	Sénia	TOTAL CATALONIA
Dams	2	5	9	8	4	1	**45**
Weirs	36	41	15	15	35	0	**740**
Gauging stations	3	5	5	0	4	0	**93**
Total	**41**	**51**	**29**	**23**	**43**	**1**	**886**

Fish passes

There were a total of 95 fish passes in Catalonia in 2010 (see Fig. 15-20 and Tables 7-9).

Restoration solutions were very scarce in the whole of Catalonia: between 2007 and 2010 at least two river obstacles were completely eliminated: a weir in the Sorreigs stream at Santa Cecilia de Voltregà (Ter river basin, Osona region), carried out by the Catalan Water Agency, and an irrigation weir in the Ripoll river at Barberà del Vallès (Besòs river basin, El Vallès Occidental region), carried out by the municipality (Fig. 14). Previously, there were only 15 known partial weir removals for environmental reasons in the upper Garona river basin (Val d'Aran region) (Fig. 14).

Partial information on restoration solutions associated with water quality (new waste water treatment plants) and river and wetlands habitat improvement projects was also obtained (see Fig. 14), but not for all areas.

In relation to the timescale, there were 78 rehabilitation solutions until 2006. Between 2006 and 2010, at least 16 new fish passes were built, 10 of them exemplary, with an ICF index of good or very good quality.

Partial information on rehabilitation solutions associated with systems for fish protection was also obtained, especially on environmental flow regimes and downstream fish migration protection (light barriers against the entrainment of fish in channels or turbines) (see Fig. 18), and fish friendly adjusted management of irrigation sluices and ship locks (as is shown at Fig. 19), but they were collected at different times and not for all areas.

Water quality improvement. Waste water treatment plant at Ribes de Freser (Freser river subbasin, Ter river basin, El Ripollès region) in 1994.

Weir removal in the Sorreigs stream (Ter river basin, Osona region) in October 2008: before (left) and after (right)

Weir removal in the Ripoll river at Barberà del Vallès (Besòs river basin, El Vallès Occidental region) in 2010: before (left) and after (right)

Partial weir removal in the Nere river at Vielha (Garona river basin, Aran valley) in 2006 (left) and in the Freser river at Ribes de Freser (Ter river basin, El Ripollès region) in 2010

Figure 15. Restoration solutions to improve river connectivity for fish in Catalonia. Pictures: Marc Ordeix – CERM, except the Sorreigs (Narcís Prat – DEUB) and the Ripoll rivers (Aleix Comas – SERPA).

Bottom ramp of the bridge of the Daró river at La Bisbal d’Empordà (El Baix Empordà region) in 2010

Fish ramp of the gauging station of the Muga river in L’Alt Empordà region in 2010

Figure 16. Rehabilitation solutions (close-to-nature fish pass) to improve river connectivity for fish in Catalonia. Pictures: Quim Pou – CERM (top) and Marc Ordeix – CERM (bottom).

Pool fish pass with vertical slots of the water supply weir on the Nere river at Vielha (Garona river basin, Aran valley) in 2006

Pool fish pass without drops at the Serrasans hydropower weir on the Llobregat river at Sallent (El Bages region) in 2010

Pool fish pass with drops of the Pontitxol weir on the Ter river at Setcases (El Ripollès region) in 2006

Deflector fish pass of the base of the bridge in Viliella stream at Lles de Cerdanya (La Llosa river sub-basin, Segre river sub-basin, Ebre river basin, La Cerdanya region) in 2006

Denil or baffle fish pass of the Mas d'Osor weir on the Espinzella stream at Viladrau (Major stream sub-basin, Ter river basin, Osona region) in 2006

Figure 17. Rehabilitation solutions (broad-spectrum technical fish pass) to improve river connectivity for fish in Catalonia.

Fish lift of the Mal Pas weir on the Romadriu or Santa Magadalena river at Llavorsí (Noguera Pallaresa river sub-basin, Ebre river basin, El Pallars Subirà region) in 2006

Figure 18. Rehabilitation solutions (a mechanical fish pass) to improve river connectivity for fish in Catalonia.

Light (stroboscopic) barriers against downstream entrainment of fish in channels and turbines. Entrance to the Industrial Channel of Manlleu, on the Ter river (Osona region) in 2012

Figure 19. A rehabilitation solution (a system for fish protection) to improve river connectivity for fish in Catalonia.

Environmental flows at Can Bros weir on the Llobregat river at Martorell (El Baix Llobregat region) in 2006

Development of a fish friendly ship lock project (Life MigratoEbre) on the Ebre river at the Xerta weir (La Ribera d'Ebre region) in 2015

Figure 20. Rehabilitation solutions (adjusted management) to improve river connectivity for fish in Catalonia.

Characterisation and rapid assessment of fish passes

During the period 2005 to 2010, a study of fish pass facilities in Catalonia (with a surface area of 32,000 km^2, in the north-east of the Iberian Peninsula) was carried out through direct inspection of 95 fishways (present in 11% of the total obstacles; Table 7). These were mostly located in the upper parts of the Ebre (Segre river sub-basin), Garona, Ter, Llobregat and other river catchments (30, 24, 18, 16 and 8 fishways, respectively; Table 8).

Val d'Aran was, by a great margin, the region with the highest number (24) (Table 9). Retro-fitted solutions using broad-spectrum technical structures, mainly pool-type fishway or pool fish pass facilities, were located. Most of them were in the Pyrenees to improve brown trout (*S. trutta*) fisheries (90%).

In the whole of Catalonia, 17 fish passes (18%) were classified as restoration solutions (two total and fifteen partial weir removals), most of which were in Val d'Aran (Pyrenees). Only 7 obstacles (7%) were rehabilitation solutions classified as close-to-nature fish passes (fish ramps). 46 (48%) were rehabilitation solutions that basically used broad-spectrum technical fish passes, specifically pool-type and vertical slot fishways. 10 (11%) rehabilitation solution broad-spectrum technical fish passes also included deflectors and baffle fish passes, and 6 (6%) smooth ramps (two of them V-flat gauging stations). Only 2 rehabilitation solutions based on mechanical fish passes were observed: two fish lifts (2%) (see Fig. 15-20 and Tables 7-9).

Table 7. Existing typologies of fish passes in the rivers of Catalonia in 2010.

Solutions			**Number**
Restoration solutions		Total obstacle removal	2
		Partial obstacle removal	15
Rehabilitation solutions	Close-to-nature fish passes	Bottom ramps or rock ramps	1
		Fish ramps	7
	Broad-spectrum technical fish passes	Pool fish passes	34
		Pool fish passes without drops	3
		Slot passes or vertical slot fish passes	9
		Deflectors	8
		Denil or baffle fish passes	2
		Smooth ramps	6
	Mechanical or specific technical fish passes	Fish lifts	2
	Other solutions not considered effective	“Stairs”	6
TOTAL			**95**

Table 8. Fish passes in the rivers of Catalonia in 2010, classified by river basin.

River basin	Number in 2010
Ebre	30
Garona	24
Ter	18
Llobregat	16
Besòs	2
Dar	2
Muga	2
Tordera	1
Fluvià	1
TOTAL	**95**

Table 9. Fish passes in the rivers of Catalonia in 2010, classified by region.

Region	Number in 2010
Alt Empordà	1
Alta Ribagorça	1
Alt Urgell	3
Anoia	1
Bages	0
Baix Ebre	3
Baix Empordà	4
Baix Llobregat	5
Berguedà	6
Cerdanya	4
Garrotxa	1
Gironès	3
Noguera	4
Osona	5
Pallars Jussà	1
Pallars Sobirà	7
Ripollès	10
Segrià	6
Selva	1
Solsonès	3
Val d'Aran	24
Vallès Occidental	2
Total	**95**

Index of river connectivity (ICF)

Using the ICF index (Solà et al., 2011), 21 of the obstacles (22%) were classified as "very good quality" and 16 (17%) as having "good" connectivity, being either partial barriers or close-to-nature fish facilities. 16 of the obstacles (17%) were considered in the "moderate" quality class, 14 (15%) were "poor" and 28 (30%) were "bad" (see Table 10 and Figure 21). According to the Framework Water Directive, only 39% of the solutions were available for fish migration. Therefore, most fish passes did not adequately address the requirements of native fish species: most of them were badly designed or poorly maintained (61% of the solutions).

Table 10. River connectivity index (ICF; Solà et al., 2011) calculated for fish passes in the rivers of Catalonia in 2010.

Categories	Quality	Score	Number of fish passes in 2010	%
I	Very good	> 95	21	22.1
II	Good	75 - 95	16	16.8
III	Moderate	50 - 74	16	16.8
IV	Poor	25 - 49	14	14.7
V	Bad	< 25	28	29.5

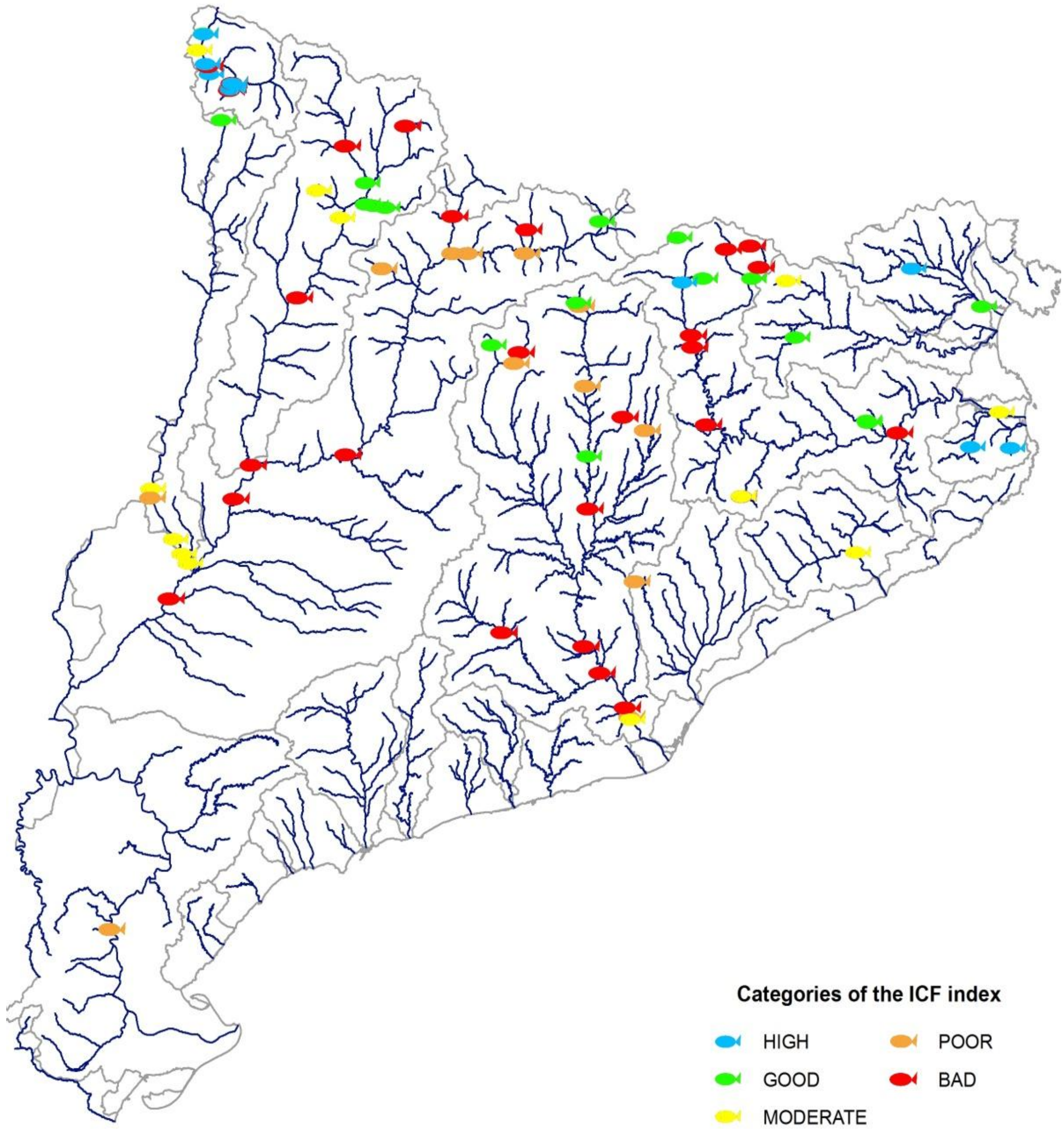


Figure 21. Fish passes in the rivers of Catalonia (NE Iberian Peninsula) in 2010, and results of the index of river connectivity (ICF) for each. Adapted from Ordeix et al., 2014.

Design, construction and maintenance problems

The major problem of the fish passes in Catalonia, which affects 46 devices of a total of 95 (48.4%), is a waterfall that is too high at the fish pass entrance from downstream, mostly produced by undermining (see Table 11 and Fig. 22e). The speed was too high and there was too much turbulence in the fish pass in 34 (35.8%) and 33 (34.7%) fish passes, respectively (see Table 11, Fig. 22g and 22h). 27 devices (28.4%) were too small or a lack of maintenance made them deficient (see Table 11, Fig. 22a and Fig. 22j).

Other single deficiencies, such as the entrance located too far from the obstacle, no mechanism preventing fish going into turbines or channels, or excessive heights of internal waterfalls, rendered 23 fish passes (24.2%) useless (see Table 11, Fig. 22d, Fig. 22f and Fig. 22k). Shallow pools in the fish pass were constructed in 20 sites (21.1%) (see Table 11 and Fig. 22i). The pond to jump from downstream to the fish pass entry was too shallow in 18 cases (19.0%) (see Table 11 and Fig. 22c). Finally, there was not enough flow at 13 fish passes (13.7%) (see Table 11 and Fig. 22b).

The main problems of the fish passes in the rivers of Catalonia are described in more detail below (and shown in Table 11, classified by river basin):

a) **The fish pass is too small**. 27 fish passes (28.4%) in Catalonia (Fig. 22a) were partially well designed but too small in relation to the full river width or the total river flow, causing a null or minimal impact on the migrating fish population.

b) **There is an absence of flow or poor attractive flow at the fish pass entrance**. Sufficient water current or turbulent flow to attract fish to the fish pass entrance, to encourage fish to continue up to the entrance, is pending at 13 sites (13.7%) (Figure 22b).

c) **The pond to jump from downstream into the fish pass entrance is too shallow**. Shallow ponds (< 0.01 m) immediately downstream of the fish pass, without insufficient depth for fish to jump was found in 18 devices (19.0%; all of them, pool fish passes), sometimes associated with lack of maintenance (Figure 22c).

d) **Entrance is too far from the obstacle**. The water outlet downstream of 23 fish passes (24.2%) was far from the obstacle, so the fish couldn't find it (Figure 22d).

e) **Waterfall is too high at the fish pass entrance from downstream, mostly produced by undermining**. Undermining associated with the water outlet of the fish pass produces, in the medium term, mismatches in the structure, such as a waterfall too high at the fish pass entrance from downstream (often between 0.50 to 0.70 m), with negative impacts on the fish pass operation. This affects 46 fish passes (48.4%) in Catalonia (Fig. 22e).

f) **Excessive heights between adjacent pools**. Designed for large swimmers or jumpers, internal excessive heights are common in 23 fish passes (24.2%). Internal water level differences are often higher than 0.30 m, and in many cases around 0.40 to 0.50 m, which is excessive for most native fish (Figure 22f).

g) **Excessive speed in the fish pass**. Excessive water speed (> 2 m/s) makes it difficult, for example, for young brown trout and most of cyprinids, especially males, which are smaller than females, to get through. This affects 34 fish passes (35.8%) in Catalonia (Fig. 22g).

h) **Too much turbulence in the fish pass**. Excessive turbulence prevents fish crossing and jumping in 33 fish passes (34.7%) in Catalonia (Fig. 22h).

i) **Shallow pools into the fish pass**. Pools with inadequate depths into the fish pass (< 0.01 m) were constructed in 20 fish passes (21.1%) (Figure 22i).

j) **Obstruction, filling or structural disrepair of the fish pass**. Even incorporating correct design and being appropriate to the characteristics of the river stretch and to their own ictiofauna, 27 fish passes (28.4%), especially broad-spectrum technical fish passes, suffer from defects that completely or severely disable them. Mostly due to lack of maintenance, entrance, exit or intermediate pool obstruction, filling with sediment and structural disrepair of the fish pass lead to inoperation (Fig. 22j).

k) **Absence of mechanisms to prevent fish going into turbines or bypass channels**. In 23 sites (24.2%), there are no mechanical (e.g. iron bars) or behavioural (such as lighting) barriers close to turbines and bypass channel entrance. This is a very important problem, especially during downstream fish migration (Figure 22k).

Although some fish passes do not include it, the existence of mechanisms to avoid predation inside the device, such as a steel grid or other kind of cover, is not considered essential. Predation of fish by aquatic birds and mammals (except invasive species) can be considered a fact of nature. Without maintenance, mechanisms to avoid predation could easily retain spam or other materials transported by water, which could lead to reducing or preventing fish migration through the fish passes.

a) Too small dimensions for the pool fish pass. Segre river at the Canal Olímpic hydropower weir, La Seu d'Urgell (Ebre river basin, La Cerdanya region)

b) Poorly regulated flow at a Denil or baffle fish pass entrance. Aigua de Valls river at Molí de Cal Sastre Barat hydropower weir, Guixers (Llobregat river basin, El Solsonès region)

c) Pond that is to shallow to jump from downstream to the pool fish pass entry. Vall d'Horta stream at Muntada irrigation weir, Sant Llorenç Savall (Besòs river basin, El Vallès Occidental region)

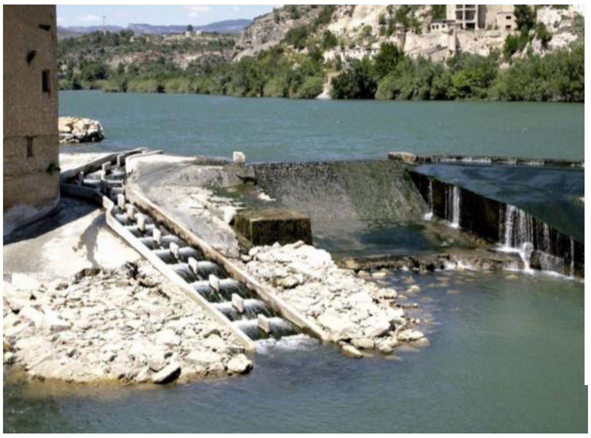
d) Fish pass entrance too far from the obstacle. Llobregat river at Molins de Rei irrigation weir (El Baix Llobregat region).

Figure 22. Several problems of fish passes in the rivers of Catalonia (NE Iberian Peninsula).

e) Waterfall too high at the pool fish pass entrance from downstream, produced by undermining. Segre river at Alòs de Balaguer hydropower dam, Camarassa (Ebre river basin, La Noguera region)

f) Excessive heights between adjacent pools. Segre river at Pardinyes hydropower and irrigation weir, Lleida (Ebre river basin, El Segrià region)

g) Excessive speed into a partial weir removal. Nere river at one of the Vielha weirs (Garona river basin, Val d'Aran region)



h) Too much turbulence in a pool fish pass. Ebre river at Xerta weir (El Baix Ebre region)

Figure 22 (bis). Several problems of fish passes in the rivers of Catalonia (NE Iberian Peninsula).

i) Shallow pools into pool passes. Anoia river at Vilanova del Camí weir (Llobregat river basin, L'Anoia region).

j) Pool fish pass without enough depth in the pools, full of gravel and pebbles, due to lack of maintenance. Finestrelles brook at Núria Sanctuary weir (Ter river basin, El Ripollès region).

k) Absence of mechanisms to prevent fish going into turbines. Ter river at El Pontitxol weir, Setcases (El Ripollès region)

Figure 22 (bis). Several problems of fish passes in the rivers of Catalonia (NE Iberian Peninsula).

Table 11. Most important problems of fish passes in the rivers of Catalonia (NE Iberian Peninsula) in 2010, classified by river basins and in total.
Legend:

A. Too small dimensions of the fish pass.
B. Absence or poor flow at the fish pass entrance.
C. Pond that is too shallow to jump from downstream to the fish pass entrance.
D. Entrance located too far from the obstacle.
E. Waterfall too high at the fish pass entrance from downstream, mostly produced by undermining.
F. Excessive heights between adjacent pools.
G. Excessive speed in the fish pass.
H. Too much turbulence in the fish pass.
I. Shallow pools in the fish pass.
J. Obstruction, filling or structural disrepair of the fish pass.
K. Absence of mechanisms to prevent fish going into turbines or bypass channels.

River basin	A	B	C	D	E	F	G	H	I	J	K	Total
Ebre	13	8	7	7	15	10	2	5	8	11	10	30
Garona	-	1	1	5	14	-	19	18	2	7	-	24
Ter	4	3	6	7	11	5	6	4	6	3	8	18
Llobregat	7	1	4	4	5	5	6	6	4	6	4	16
Besòs	-	-	-	-	-	1	-	-	-	-	1	2
Daró	-	-	-	-	-	-	-	-	-	-	-	2
Muga	1	-	-	-	1	1	-	-	-	-	-	2
Tordera	1	-	-	-	-	1	1	-	-	-	-	1
Fluvià	-	-	-	-	-	-	-	-	-	-	-	1
TOTAL	**27**	**13**	**18**	**23**	**46**	**23**	**34**	**33**	**20**	**27**	**23**	**95**
%	**28.4**	**13.7**	**19.0**	**24.2**	**48.4**	**24.2**	**35.8**	**34.7**	**21.1**	**28.4**	**24.2**	**-**

“In situ” assessment of 10 fish passes

Study sites

10 selected fish passes were located at hydropower weirs (4), gauging stations (5) and an irrigation weir (1) (see Fig. 23):

- 5 in the Ter river basin (2 hydropower weirs, 2 gauging stations and 1 irrigation weir),
- 2 in the Ebre river basin (2 hydropower weirs),
- 2 in the Llobregat river basin (2 gauging stations), and
- 1 on the Tordera river (1 gauging station).

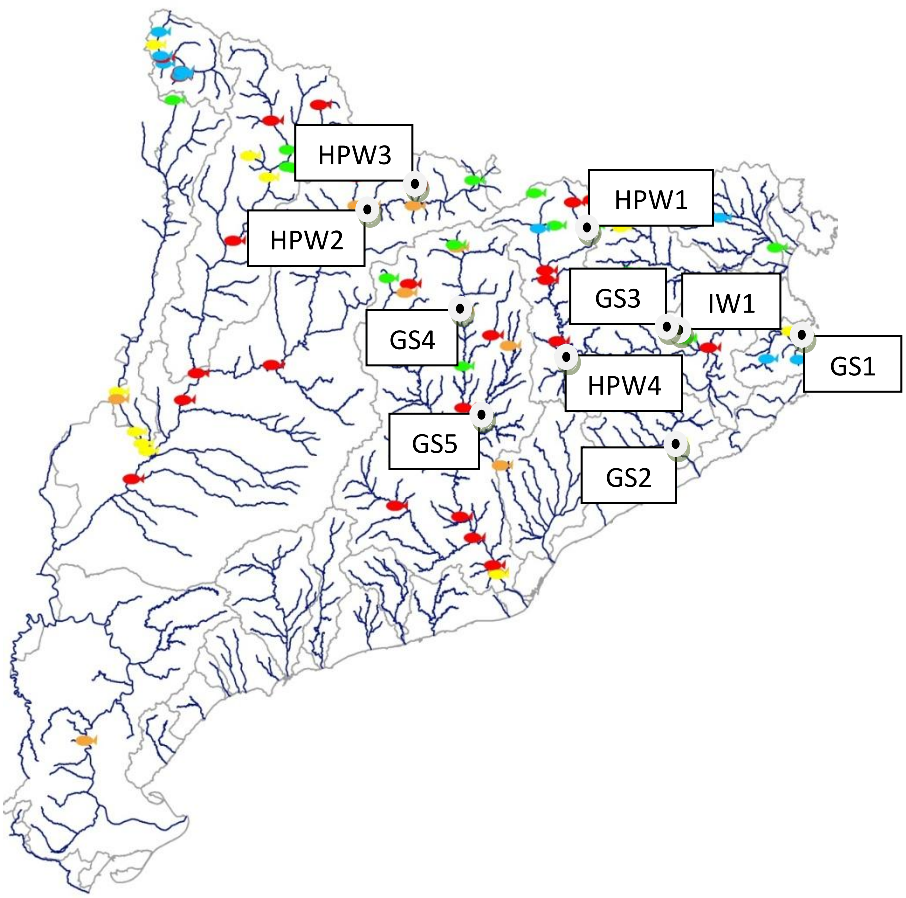


Figure 23. Location of the 10 selected fish passes assessed “in situ” (black dot) on the map of the fish passes in the rivers of Catalonia (NE Iberian Peninsula) in 2010. Legend: HPW: hydropower weir, GS: gauging station, IW: irrigation weir.

1. Upper Ter river at the hydropower weir of Les Rocasses, at Camprodon (El Ripollès region) (HPW1)

The Rocasses weir is 17 m long and 2.3 m high. It is located in a river stretch associated with an extremely high density of weirs and other obstacles. The fish pass consists of a pool fish pass without small waterfalls in a rock ramp. The fish pass is integrated into a rock ramp with a triple function: to ensure its structural strength at times of high flow, to achieve good landscape integration, and to permit the passage of semiaquatic animals (some macroinvertebrates, amphibians, reptiles and mammals).

Fish crossing rates and size class frequencies were estimated through a combination of fish trapping at the water intake upstream of the facility, electrofishing upstream and downstream and group mark-recapture methods using a total of 3,000 fish tagged with acrylic paint. Surveys were performed during seven periods of ten days every two months in 2006/2007 (from February to February). A cross-section of the fish pass was completely blocked off using a special fish trap (3.5 m long, 0.01 m mesh size) with a tight connection to the bottom. The group mark-recapture method employed an acrylic paint injection system in the caudal fin of the fish. The fish caught on each side of the obstacle were marked with different colours (blue upstream, red downstream). Mark-recapture models (Larinier *et al*., 1994) allow estimation of fish crossing rates between two fisheries as the percentage of units located downstream of the device to travel upstream of the device during this period. Application of group mark-recapture methods has enabled the calculation of fish crossing rates for brown trout.

Figure 24. The Ter river downstream of Les Rocasses weir at Camprodon (El Ripollès region). May 2006.

Figure 25. The fish pass (a pool fish pass without drops) of Les Rocasses weir at Camprodon (Ter river, El Ripollès region). May 2006.

Figure 26. Special fish trap blocking the cross-section of the fish pass of Les Rocasses weir, at Camprodon (Ter river, El Ripollès region) (left), and after electrofishing (right). October 2006. Pictures: Marc Ordeix – CERM (left) and Èlia Bretxa – CERM (right).

2. Lower Ter river at the Torroella de Montgrí bridge gauging station (EA080) (El Baix Empordà region) (GS1)

The Torroella de Montgrí bridge base is 125 m long and 1 m high and is the first significant obstacle in the Ter river for fish migrating upstream from the Mediterranean Sea, in addition to being associated with frequent low flow conditions. The fish pass is a pool fish pass integrated into a gauging station. It includes traverses of variable size, mainly less than 0.25 m in height, although there are some higher than 0.6 m.

Surveys were performed during seven periods of ten days every two months in 2006 (from January to September). At this site, fish crossing rates were estimated using fish trapping at the water intake upstream of the facility and by performing visual counts, while the size class frequencies upstream and downstream of the obstacle were estimated by electrofishing. Two special fish traps (2 × 0.8 m rectangular stainless steel squares, 7 m long and with a 0.015 m mesh size) were installed immediately upstream of the two water intakes upstream of the facility. Visual counts consisted of 10-minute censuses repeated every 1.5 hours throughout the day. Total counts were performed from a point with an optimal viewing angle, supported by digital video recording to validate the visual counts.

Figure 27. The Ter river upstream of the Torroella de Montgrí gauging station (El Baix Empordà region) on 7th May 2005.

Figure 28. The obstacle and the fish pass (a pool fish pass) of the Torroella de Montgrí gauging station (Ter river, El Baix Empordà region). May 2006.

Figure 29. Special fish traps blocking the cross-sections of the fish pass of the Torroella de Montgrí gauging station (Ter river, El Baix Empordà region). May 2006.

3. Upper Segre river (Ebre river basin) at the Olympic channel of La Seu d'Urgell hydropower weir (L'Alt Urgell region) (HPW2)

This weir is 70 m long and 1 m high. The fish pass is a broad-spectrum technical pool fish pass.
Its traverses are only 0.1 m in height, and the fish pass is only 0.75 m wide. Fish crossing rates and size class frequencies were estimated by combining fish trapping at the water intake upstream of the facility (3.5 m long, 0.01 m mesh size, with a tight connection to the bottom), and electrofishing upstream and downstream of the obstacle.

Surveys occurred in 2008 (April, July and November) in three-week periods every three months. A fish trapping campaign was conducted during each monitoring period simultaneously using two kinds of fish traps without bait: *camaronera* (2 m long, 0.006 m mesh size) and *anguilera* (3.5 m long, 0.01 m mesh size). However, electrofishing was only performed in July because of the existence of many deep pools.

Figure 30. The Segre river downstream of the Olympic channel of La Seu d'Urgell hydropower weir (L'Alt Urgell region). 11th April 2007.

Figure 31. The obstacle and the fish pass (a pool fish pass) of the Segre river at the Olympic channel of La Seu d'Urgell hydropower weir (L'Alt Urgell region). 11th April 2007.

Olympic channel of La Seu d'Urgell hydropower weir (L'Alt Urgell region) (left), and electrofishing downstream of this weir (right). 11th April 2007. Pictures: Marc Ordeix – CERM (left) and Núria Sellarès - CERM (right).

4. Aravó or Querol stream (Ebre river basin) at the Reial Club de Golf de la Cerdanya hydropower weir, at Colònia Simon, Puigcerdà (La Cerdanya region) (HPW3)

This weir is 40 m long and 1 m high. The fishway is a broad-spectrum technical structure consisting of a deflector with 0.20 m high baffles. Fish crossing rates and size class frequencies were estimated through a combination of fish trapping at the water intake upstream of the facility (3.5 m long, 0.01 m mesh size, with a tight connection to the bottom), and electrofishing upstream and downstream of the obstacle.

Surveys occurred in 2008 (April, July and November) in three-week periods every three months. A fish trapping campaign was performed in each monitoring period using *anguilera* traps (3.5 m long, 0.01 m mesh size). However, electrofishing was only conducted in July because of the existence of many deep pools.

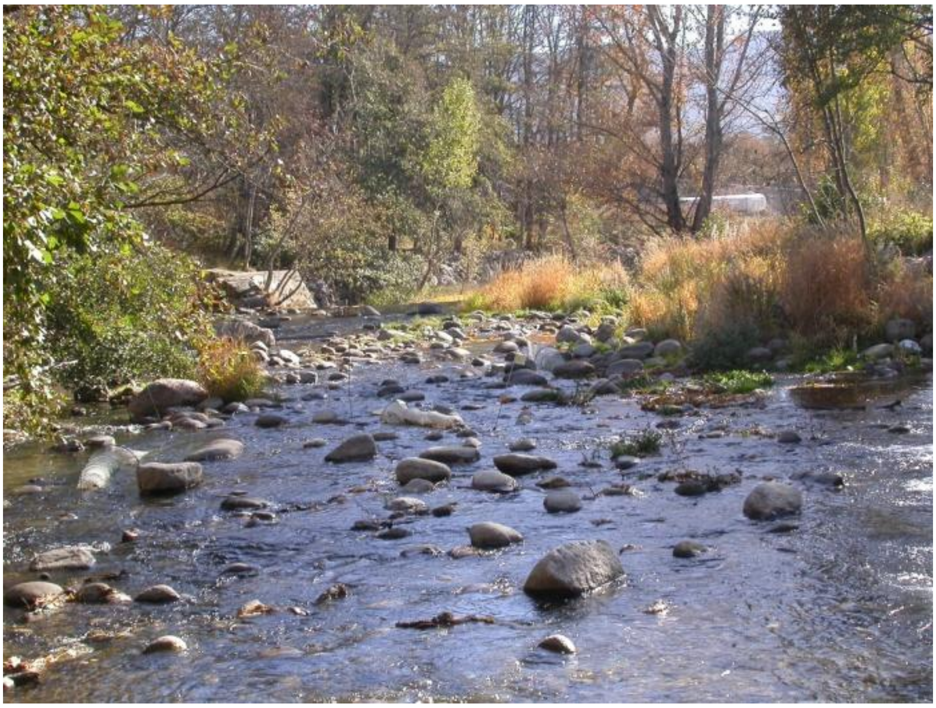


Figure 33. The Aravó or Querol river downstream of the Reial Club de Futbol de la Cerdanya weir, at Colònia Simon, Puigcerdà (La Cerdanya region). 9th November 2008.

Figure 34. The obstacle and the fish pass (with deflectors) of the Reial Club de Futbol de la Cerdanya weir, at Colònia Simon, Puigcerdà (La Cerdanya region). 2nd November 2006. Pictures: Núria Sellarès - CERM.

Figure 35. Special fish traps blocking the cross-section of the Reial Club de Futbol de la Cerdanya weir, at Colònia Simon, Puigcerdà (La Cerdanya region). April 2007 (left) and 2nd July 2007 (right).

5. Low Tordera river at the Fogars de la Selva gauging station (EA089) (La Selva region) (GS2)

The Tordera river gauging station is 72 m long and 0.5 m high. It is the first significant obstacle in this river for fish coming upstream from the sea. The fish pass is a ramp integrated into the gauging station. This river reach dries up every year for a duration ranging from several weeks to several months in summer, and low flow conditions (< 0.5 m^3/s) dominate during the rest of the year, although there are also flood periods.

Monitoring was undertaken immediately after the high flood period (> 10 m^3/s). Fish crossing rates and size class frequencies were estimated through a combination of fish trapping at the water intake upstream of the facility and electrofishing upstream and downstream of the obstacle.

Surveys were performed in 2007 (May) and 2008 (April) in two periods of seven days each year, involving the installation of two special fish traps (2 × 0.8 m rectangular stainless steel square, 7 m long with a 0.015 m mesh size) immediately upstream of the two water intakes upstream of the facility and electrofishing upstream and downstream of the obstacle.

Figure 36. The Tordera river downstream of Fogars de la Selva gauging station (La Selva region). 15th May 2007.

Figure 37. The weir and the fish pass (a fish ramp) of Fogars de la Selva gauging station (La Selva region). 15th May 2007.

Figure 38. Eel ramp and special fish trap blocking the cross-section of the fish pass of Fogars de la Selva gauging station (La Selva region). April 2008.

6-7. La Llémena stream (Ter river basin) at the Sant Gregori gauging station (EA009) (GS3) and the Sant Gregori gardens irrigation weir (IW1), at Ginestar de Llémena (El Gironès region)

The gauging station weir is 6.5 m long and 1 m high. It includes a broad-spectrum technical pool fish pass with 7 traverses between 0.1 and 0.2 m high. The depth of the pools was improved in 2009, and a complementary concrete eel ramp was also constructed. The Sant Gregori gardens irrigation weir, located 600 m downstream of the gauging station, is 7 m long and 2 m high. The passage system is a close-to-nature fish pass consisting of a natural fish ramp with a 5% slope.

Here, the fish crossing rates and size class frequencies were estimated by combining fish trapping at the water intake upstream of the facilities, electrofishing upstream and downstream and marking with individual mark-recapture methods (PIT tags). A cross-section of the fish passes was completely blocked off using special fish traps (3.5 m long, 0.01 m mesh size) with a tight connection to the bottom. Application of individual mark-recapture methods enabled the calculation of specific fish crossing rates. Surveys were conducted in 2008/2010 (from March to November) in six periods of twelve days every four months. Moreover, an additional campaign of fish trapping upstream and downstream of the obstacle was performed to increase the fish catch for tagging in July 2008. Micromarks consisting of PIT tags (diameter: 0.002 m, length: 0.012 m, and frequency: 134.2 kHz) were inserted into the peritoneal cavities of 1,133 fishes (1,023 Western Mediterranean barbels, 80 Ebro barbels and 30 eels). Western Mediterranean barbels (*Barbus meridionalis*) with minimum length of 0.09 m, Ebro barbels (*Luciobarbus graellsii*) larger than 0.1 m and European eel (*A. anguilla*) larger than 0.3 m were marked. Fixed receivers (square antennas of 0.30 × 0.80 m) identified fish individually and continuously and allowed us to obtain information regarding when they advanced to the water intake upstream of the fish pass. In addition, portable receivers allowed identification of each tagged fish (using the incorporated encoded chip) when it was recaptured.

Figure 39. The Llémena stream upstream of the Ginestar de Llémena gauging station at Sant Gregori (Ter river basin, El Gironès region) (top), between this gauging station and the irrigation weir of the vegetable gardens of Sant Gregori (middle), and downstream of this irrigation weir (bottom). 25th May 2010.

Figure 40. The weir and the fish pass (a pool fish pass with an eel ramp) of the Ginestar de Llémena gauging station at Sant Gregori (Ter river basin, El Gironès region) (top and middle right), and the obstacle and the fish pass (a fish ramp) of the irrigation weir of the vegetable gardens of Sant Gregori (middle left and bottom). 25th May 2010.

At these sites, it was possible to estimate fish passage rates for each species, which was also weighted by population size using the results from the depletion electrofishing survey. Moreover, identification of each marked specimen within the fish pass device provided information on the phenology of fish migration and biometric characteristics of individuals that successfully used the fishway.

Figure 41. PIT tag rectangular antenna and special fish traps blocking the cross-section at the water intake upstream of the fish pass of the Llémena stream gauging station at Ginestar de Llémena (Ter river basin, Sant Gregori municipality, El Gironès region) (top), and irrigation weir of the vegetable gardens of Sant Gregori (bottom). 25th May 2010.

8. The Llobregat river at Cal Rosal gauging station (EA066), at Olvan (El Berguedà region) (GS4)

The gauging station of the Llobregat river at Olvan is 32 m long and 0.7 m high. It is a V-flat, which includes a smooth ramp (with a 10% slope); theoretically, it is a fish pass by itself.

Fish crossing rates were estimated using fish trapping at the water intake upstream of the facility, while the size class frequencies upstream and downstream of the obstacle were estimated by electrofishing. Surveys were performed in June 2010 (7th-23rd, over 16 days) involving the installation of a special fish trap (2.0 x 0.8 m rectangular stainless steel squares, 7 m long and with a 0.015 m mesh size) installed immediately upstream of the facility (see Fig. 43). A big flood on 14th June (passing from an average of 9 to 22 m^3/s) affected the monitoring period: the fish trap operated correctly only for the first nine days.

No further observation was carried out due to lack of fish (upstream and downstream) associated with the poor quality of the river habitat (through predominance of mud from La Baells reservoir).

Figure 42. The Llobregat river upstream of Cal Rosal gauging station at Olvan (El Berguedà region). 7th June 2010.

Figure 43: Weir and fish pass (a V-flat) of Cal Rosal gauging station on the Llobregat river at Olvan (El Berguedà region). 7th June 2010.

Figure 44. Special fish trap blocking the cross-section of Cal Rosal gauging station on the Llobregat river at Olvan (El Berguedà region). 7th June 2010.

9. The Merlès stream (Llobregat River basin) at the Puig-reig gauging station (EA110) (El Berguedà region) (GS5)

The Merlès stream gauging station is 8 m long and 0.36 m high. Located on a river stretch with a low density of obstacles, it is a V-flat, which includes a smooth ramp with a 30% slope; theoretically, it is a fish pass by itself.

Fish crossing rates and size class frequencies were estimated through a combination of fish trapping at the water intake upstream of the facility, and electrofishing upstream and downstream. Surveys were performed between 19th October and 5th November 2010 (over 18 days). A cross-section of the fish pass was completely blocked off using a special fish trap (3.5 m long, 0.01 m mesh size) with a tight connection to the bottom.

No further observation was carried out due to lack of funds.

Figure 45. The Merlès stream downstream of the Puig-reig gauging station (Llobregat river basin, El Berguedà region). October 2010.

Figure 46: The fish pass (a V-flat) of the Merlès stream gauging station at Puig-reig (Llobregat river basin, El Berguedà region). 19th October 2010.

Figure 47. Special fish trap blocking the cross-section of the fish pass of the Merlès stream gauging station at Puig-reig (Llobregat river basin, El Berguedà region) (left) and just before starting electrofishing downstream of this gauging station (right). 19th October 2010.

10. The Ter river at La Teula hydropower weir (Manlleu, Osona region) (HPW4)

La Teula hydropower weir is 90 m long and 2.5 m high, including a canal on the left river bank. It is located on a river stretch associated with an extremely high density of weirs: 20 weirs in 25 km (1 weir each 840 m). The fish pass consists of a fish ramp 72.7 m long and 10 m wide, with a 3.9% slope, on the right river bank.

Surveys were performed in two periods: between 13th March and 31st May 2012 (over 77 days) and between 10th and 23rd May 2014 (over 12 days). It involved the installation of a special fish trap (0.8 m rectangular stainless steel square, 7 m long with a 0.015 m mesh size) at the water intake upstream of the facility. The size class frequencies downstream of the obstacle were estimated by electrofishing.

Figure 48. La Teula hydropower weir and the Ter river at Manlleu (Osona region). May 2010. Picture: Adrià Costa – Osona.com.

Figure 49: The fish pass (a fish ramp) at La Teula hydropower weir, on the Ter river at Manlleu (Osona region). May 2010.

Figure 50. Special fish trap blocking the cross-section of the fish pass at La Teula hydropower weir, on the Ter river at Manlleu (Osona region), and electrofishing downstream of this weir. May 2010. Pictures: Marc Ordeix – CERM (left) and Èlia Bretxa – CERM (right).

Results of the “in situ” assessment of 10 fish passes

1. Upper Ter river at the hydropower weir at Les Rocasses, Camprodon (El Ripollès region) (HPW1)

Here, the fish community consisted of brown trout (*S. trutta*) and Western Mediterranean barbel (*B. meridionalis*) (Fig. 51). Brown trout presents a certain morphological variation, the prevailing Mediterranean morphotype, including less than one third of Atlantic and intermediate morphotypes (following APARICIO et al., 2005). Although Catalan chub (*S. laietanus*) and European eels (*A. anguilla*) potentially exist in this reach, they were not found in this study. There were no alien fish species observed. Brown trout exhibited a maximum crossing rate in autumn (2.0-5.7 individuals/day; 0.7-1.9 % of the total migrators/day), lower in summer (1.9 ind./day; 0.8 % of the total migrators/day) and lowest in winter (0-1.2 ind./day; 0-1.4 % of the tot. migr./day) and spring (0.2 ind./day; 0.1% of the tot. migr./day). Significant movements of brown trout were mostly associated with the spawning period (around November) and in a short period just after a high flow (60 m$^{3/}$s in February 2006; crossing rate of 1.4% of the total migrants/day during next week). This hydropower station (even including this fish pass) seems to have a clear barrier effect for most of the young-of-the-year fish (YOY; fork length: FL < 0.15 m; Fig. 52). Moreover, only the largest Western Mediterranean barbel individuals (FL > 0.13 m) were able to cross upstream, most of which were females, although the differences of fish structure on each side of the barrier were not significant in October (Fig. 53).

Western Mediterranean barbel (*Barbus meridionalis*) Brown trout (*Salmo trutta*) –Mediterranean biotype-

Figure 51. Two native fish caught in the Ter river at Camprodon (El Ripollès region, Catalonia) in 2006.

Furthermore, comparison of the size structure of brown trout on each side of the weir did not indicate significant differences, except in May (Fig. 54). Fish pass effectiveness at this obstacle was considered moderate.

In addition, the use of mark-recapture models with brown trout allowed for some additional estimates of crossing rates and of total density and served to check the degree fidelity to the stretch of river where individuals were marked, except during the reproductive period.

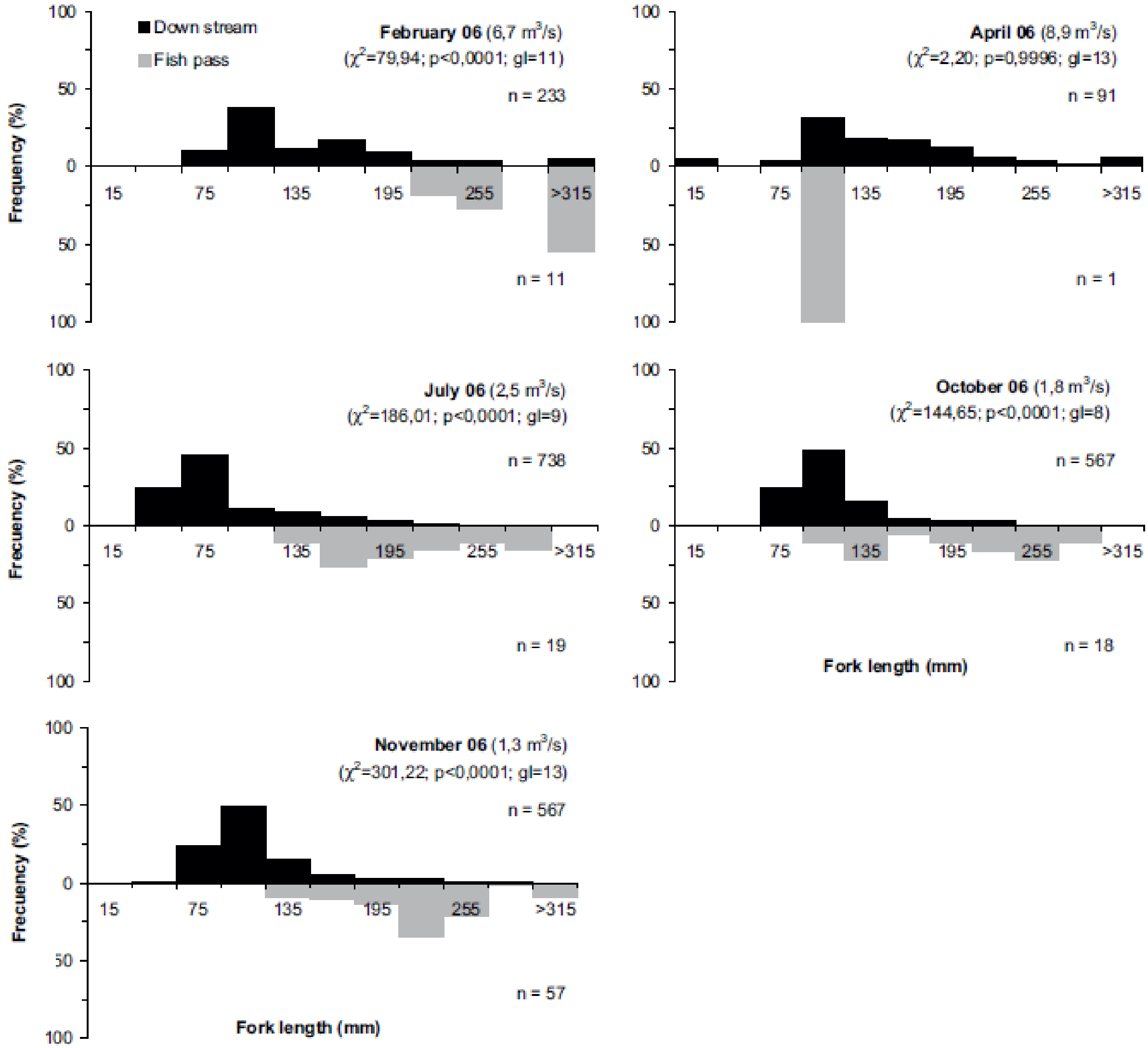


Figure 52. Brown trout (*Salmo trutta*) size class frequencies (fork length, mm) downstream and in the water intake upstream of the fish pass of Les Rocasses hydropower weir (HPW1) on the upper Ter river at Camprodon (El Ripollès region) in February, July and November 2006 (Ordeix *et al*., 2011). Flow data for each season and Chi-square test results are also shown.

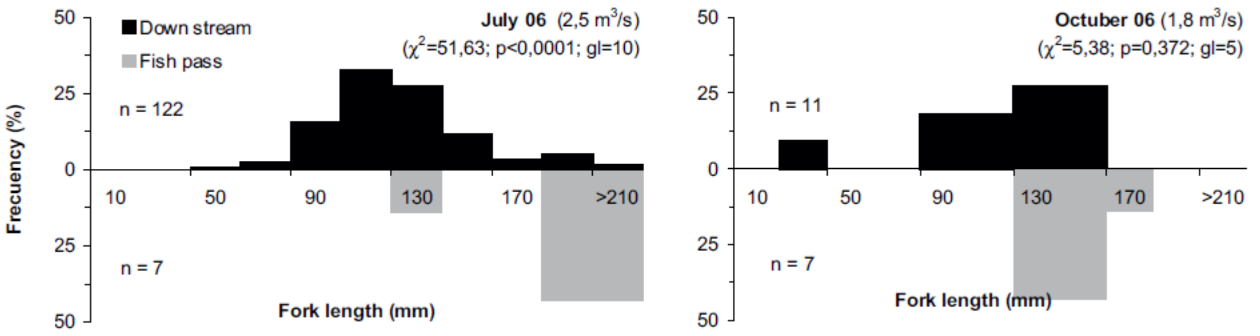


Figure 53. Western Mediterranean barbel (*Barbus meridionalis*) size class frequency (fork length, mm) downstream and in the water intake upstream of the fish pass of Les Rocasses hydropower weir (HPW1) on the upper Ter river at Camprodon (El Ripollès region, Catalonia) in July and October 2006 (Ordeix *et al*., 2011). Estimated flow data for each season and Chi-square test results are also shown.

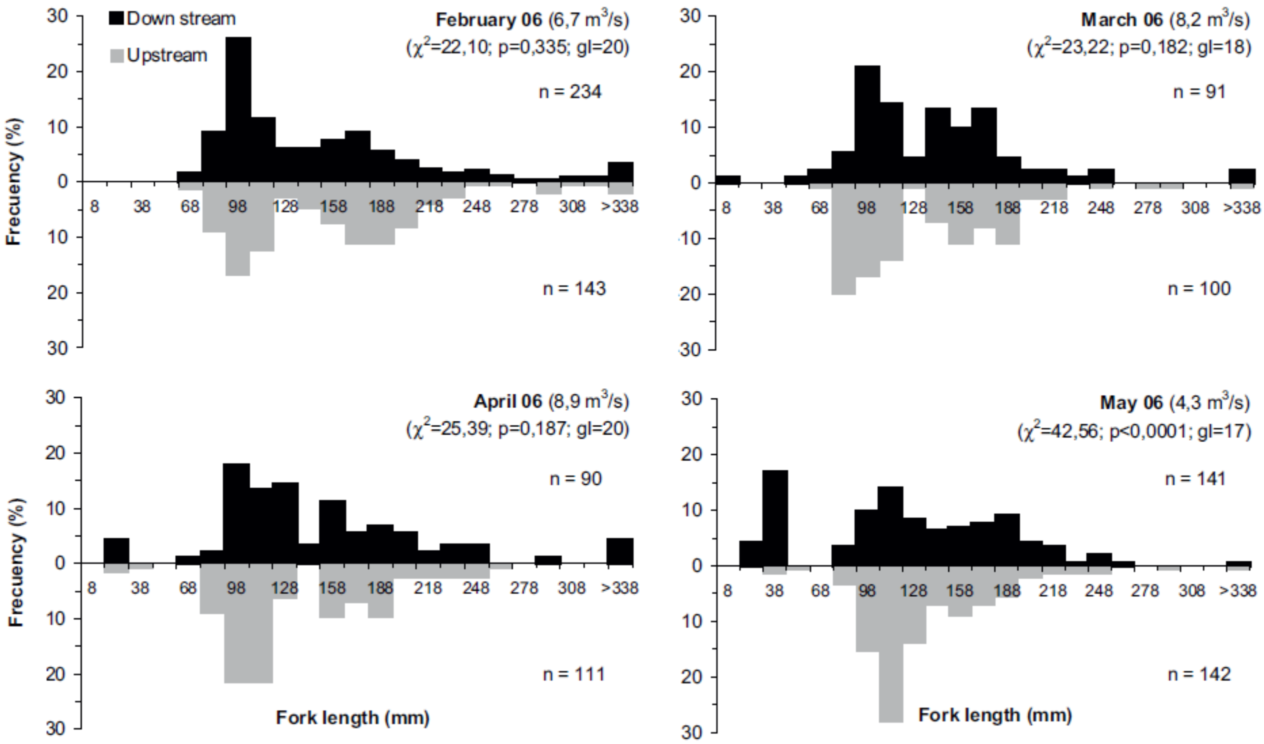


Figure 54. Brown trout (*S. trutta*) size class frequencies (fork length, mm) downstream and upstream of the fish pass at Les Rocasses hydropower weir (HPW1) on the upper Ter river at Camprodon (El Ripollès region, Catalonia) from February to May 2006 (Ordeix *et al*., 2011). Estimated flow data for each season and Chi-square test results are also shown.

2. Lower Ter river at the Torroella de Montgrí bridge gauging station (EA080) (El Baix Empordà region) (GS1)

The fish community in this river section was composed of thinlip grey mullet (*Liza ramada*), flathead grey mullet (*Mugil cephalus*), thicklip grey mullet (*Chelon labrosus*; Fig. 55), freshwater blenny (*Salaria fluviatilis*) and European eel (*A. anguilla*). Ten alien species, including Ebro barbel (*L. graellsii*), were also present.

Only large mullet and Ebro barbel (minimum size is FL > 0.55 m) individuals could cross upstream in spring after moderate floods (approximately 10 m^3/s) with a moderate water velocity inside the fish pass (< 1.4 m/s) and when water temperature was above 10°C.

A substantial improvement in the fish pass was observed on 10th April 2006, when two interior planks, which were taller than 0.60 m, were substituted by two of 0.30 m located in series. This created a new jump of 0.36-0.38 m (in comparison to around 0.60 m) and the rest were around 0.25 m high, immediately increasing the fish crossing rates at this pool fish pass. The average fish crossing rate was at a minimum (0 ind./day) from January to March and moderate from April to September (maximum of 82 mullet/day and 4 Ebro barbel/day).

Figure 55. Large school of thinlip grey mullet (*L. ramada*) and flathead grey mullet (*M. cephalus*) in the Ter river downstream of the gauging station (GS1) at Torroella de Montgrí (El Baix Empordà region, Catalonia), trying to cross this obstacle on 10th April 2006 (left), and thinlip grey mullet caught in the fish trap placed at the outlet upstream of the fish pass (right).

Visual counts revealed major activity early in the morning and in the afternoon (Fig. 56). Visual observations also showed a high concentration of glass eel downstream of this barrier, although some of these individuals might be able to migrate through the bridge base.

According to these results, the fish pass effectiveness at this obstacle has been considered moderate; only some of the fish groups and individuals present downstream of the obstacle can pass in any hydrological conditions, although the fish species size frequencies downstream and upstream are similar. Thus, there exists a barrier effect that indicates that this fish pass might not be completely functional.

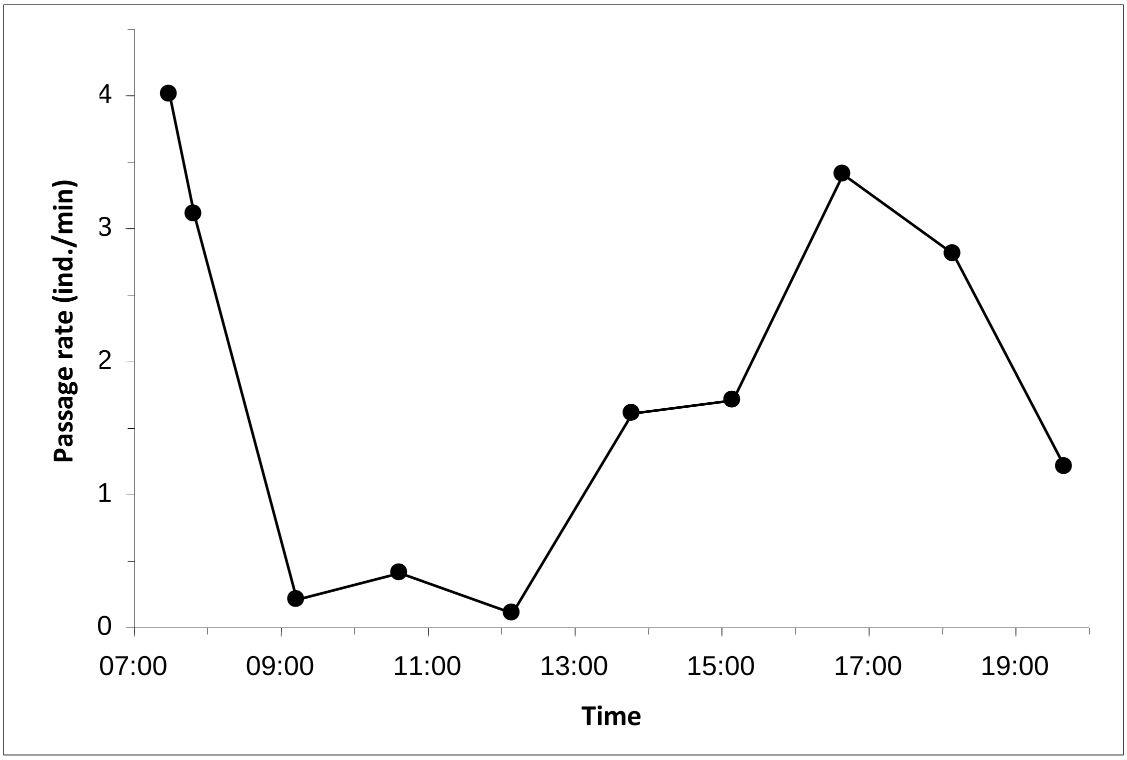


Figure 56. Passage rate upstream of big fish (thinlip grey mullet (*L. ramada*), flathead grey mullet (*M. cephalus*) and Ebro barbel (*L. graellsii*) > 200 mm) at the Ter river gauging station (GS1) at Torroella de Montgrí (El Baix Empordà region, Catalonia) on one day (10th April 2006) (Ordeix et al., 2009b).

3. Upper Segre river (Ebre river basin) at the Olympic channel of La Seu d'Urgell hydropower weir (L'Alt Urgell region) HPW2)

The fish community here consisted of brown trout (*S. trutta*), Ebro barbel (*L. graellsii*), Iberian redfin barbel (*Barbus haasi*), Catalan chub (*S. laietanus*), Ebro nase (*Parachondrostoma miegii*), Pyrenean gudgeon (*Gobio lozanoi*), Pyrenean minnow (*Phoxinus bigerri*) and Pyrenean stone loach (*Barbatula guinardi*). European eels (*A. anguilla*) and other native species may also be present (Fig. 57). Only a few individual specimens of alien fish species were found.

The maximum passage rate at this location was observed during July (16 ind./s) and was directly related to the maximum activity of cyprinid species, warm water temperature (18.7°C), low water velocity inside the fish pass (max. of 0.5 m/s) and the largest change in observed river flow (from 0.04 m^3/s on 07/07/03 to 0.3 m^3/s on 07/07/05), which was related to the irregular management of the flows of the hydropower plant (Fig. 58). The minimum passage rate (zero) occurred during November and was related to a very low flow in the river (0.03 m^3/s). In April, an intermediate passage rate was observed (5.5 ind./day).

Most of the fish species and individuals present can use the existing fish pass, as can species of smaller size, such as the Pyrenean gudgeon and Pyrenean minnow, although in both cases there appears to be a significant barrier effect for the smaller size classes (Fig. 59). Due to its small size and management of the river flow, fish pass effectiveness at this obstacle has been considered moderate.

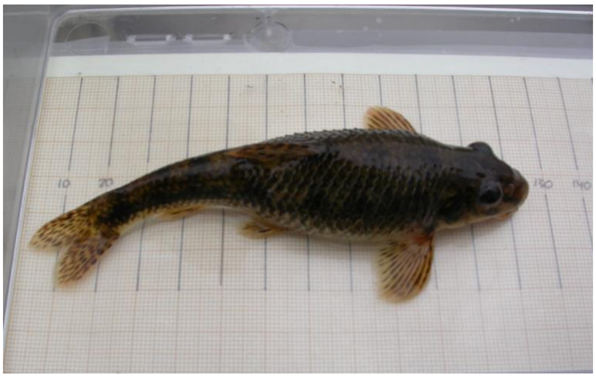
Brown trout (*Salmo trutta*)

Catalan chub (*Squalius laietanus*)

Iberian redfin barbel (*Barbus haasi*)

Ebro barbel (*Luciobarbus graellsii*)

Ebro nase (*Parachondrostoma miegii*)



Pyrenean gudgeon (*Gobio lozanoi*)

Pyrenean minnow (*Phoxinus bigerri*)

Pyrenean stone loach (*Barbatula quignardi*)

Figure 57. Several native fish caught in the Segre river at La Seu d'Urgell (Ebre river basin; L'Alt Urgell region, Catalonia) in April and July 2007.

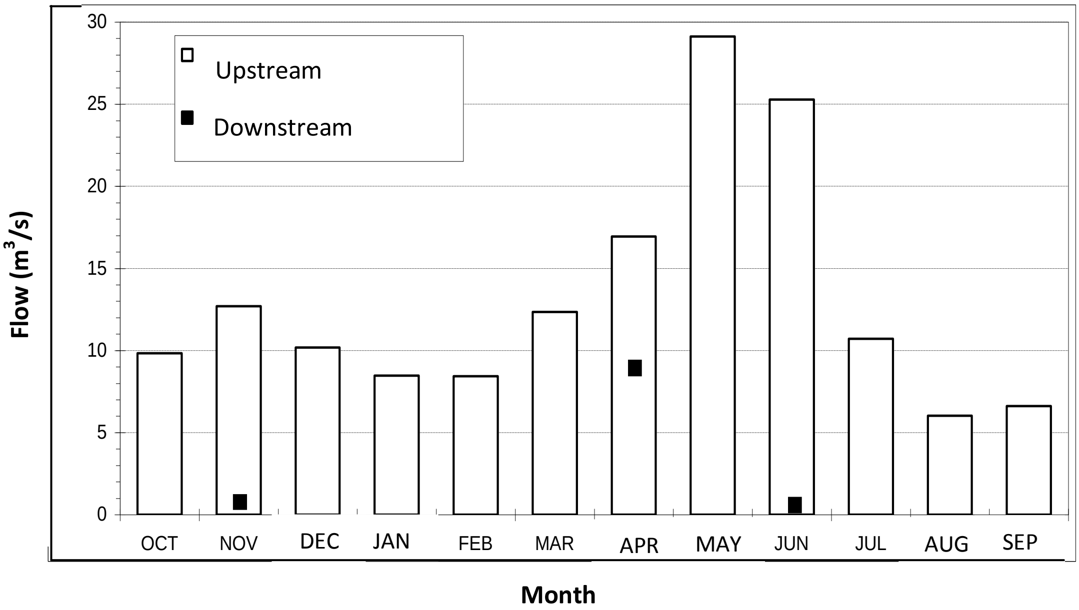


Figure 58. Monthly flows of the Segre River at La Seu d'Urgell (Ebre river basin, L'Alt Urgell region, Catalonia), upstream and downstream of the Canal Olímpic weir during the fish pass monitoring of 2007 (Ordeix et al., 2009b). From: Confederación Hidrográfica del Ebro (gauging station 23; upstream) and author's unpublished data (downstream).

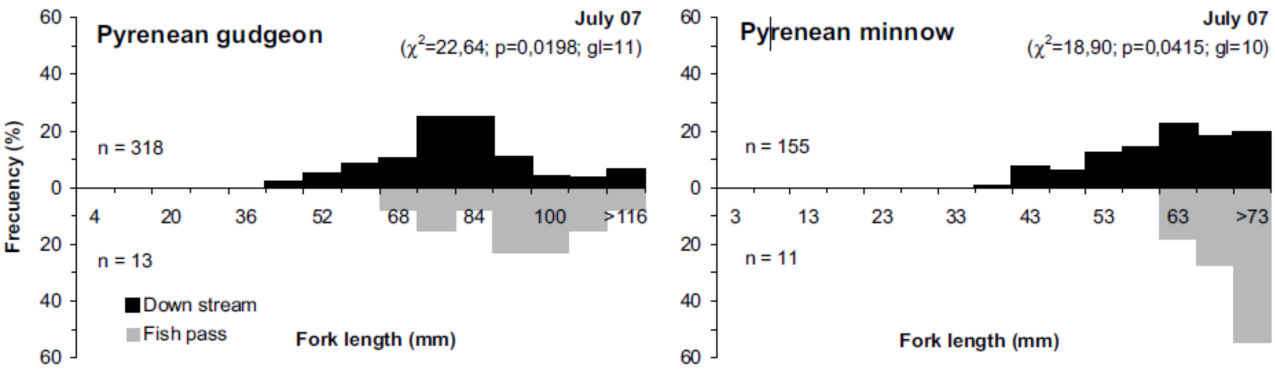


Figure 59. Pyrenean gudgeon (*Gobio lozanoi*) and Pyrenean minnow (*Phoxinus bigerri*) size class frequencies (fork length, mm) downstream and in the water intake upstream of the fish pass of the Olympic channel at La Seu d'Urgell hydropower weir (HPW2) at the upper Segre river (Ebre river basin; L'Alt Urgell region, Catalonia) in July 2007 (Ordeix *et al.*, 2011). Chi-square test results are also shown.

4. Aravó or Querol stream (Ebre river basin) at the Reial Club de Golf de la Cerdanya hydropower weir, at Colònia Simon, Puigcerdà (La Cerdanya region) (HPW3)

The fish community here consisted of brown trout (*S. trutta*), Pyrenean gudgeon (*G. lozanoi*) and Pyrenean stone loach (*B. guinardi*) (Fig. 60). No alien fish species were observed. Brown trout dominated this river stretch in terms of the number of individuals and always represented more than 92% total catches. The average rate of brown trout passage was < 1.5 ind./day, for periods with low water velocities inside the fish pass (max. of 0.5 m/s in April and 0.85 in July), and it was zero in November, when there was moderate water velocity inside the fish pass (max. of 1.41 m/s). The fish pass at this weir permits upstream migration of brown trout, although a portion of the young-of-the-year (FL > 0.10 m; Fig. 61) cannot cross upstream, even under low flow conditions (< 0.1 m^3/s).

Furthermore, comparison of the size structure of brown trout on each side of the barrier did not indicate significant differences. According to these results, fish pass effectiveness at this obstacle was considered good; the majority of the fish species and individuals present downstream of the obstacle can pass in nearly any hydrological situation, and fish species size frequencies downstream and upstream are similar. Taken together, these findings indicate that a small barrier effect exists.

Brown trout (*Salmo trutta*)

Pyrenean gudgeon (*Gobio lozanoi*)

Figure 60. Two native fish caught in the fish trap placed at the outlet upstream of the fish pass of the Aravó river at Puigcerdà (Ebre river basin; La Cerdanya region, Catalonia) in July 2007.

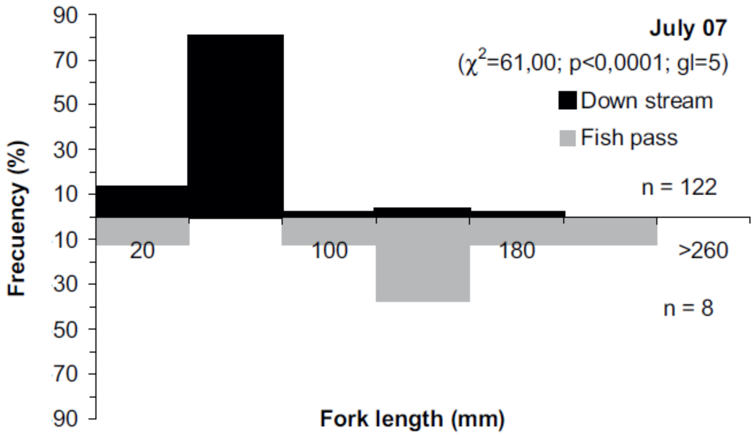


Figure 61. Brown trout (*S. trutta*) size class frequencies (fork length, mm) downstream and in the water intake upstream of the fish pass of the Reial Club de Golf de la Cerdanya hydropower weir (HPW3) on the Aravó stream at Puigcerdà (river basin; Segre river sub-basin; La Cerdanya region, Catalonia) in July 2007 (Ordeix *et al.*, 2011). Chi-square test results are also shown.

5. Low Tordera river at the Fogars de la Selva gauging station (EA089) (La Selva region) (GS2)

The fish community here consisted of Western Mediterranean barbel (*B. meridionalis*), Catalan chub (*S. laietanus*), mullets (*L. ramada*, *M. cephalus* and *C. labrosus*) and European eel (*A. anguilla*) (Fig. 62). Many alien species were also present in abundance.

The upstream migration rates of Western Mediterranean barbel and Catalan chub were 1.4 individuals/day in May and April of consecutive years, coinciding with high cyprinid activity and with moderate water velocity inside the fish pass (max. of 1.9 m/s in April) just after high flows (>10 m^3/s). Eels were not observed crossing the fish pass, but the thin eel ramp was not assessed during this study. This species was very rare upstream.

The fish pass effectiveness at this obstacle was considered moderate. Only some of the fish groups and individuals present downstream of the obstacle can pass in any hydrological condition, although the fish species size frequencies downstream and upstream are similar. There is a barrier effect indicating that this fish pass might not be completely functional.

Western Mediterranean barbel (*Barbus meridionalis*)

Catalan chub (*Squalius laietanus*)

Figure 62. Two native fish caught at the fish trap placed at the outlet upstream of the fish ramp of the gauging station of the Tordera river at Fogars de la Selva (La Selva region, Catalonia) in June 2007-2008.

6-7. The Llémena stream (Ter river basin) at the Sant Gregori gauging station (EA009) (GS3) and the Sant Gregori gardens irrigation weir (IW1), at Ginestar de Llémena (El Gironès region)

The fish community was dominated by Western Mediterranean barbel (*B. meridionalis*) and also included European eels (*A. anguilla*) and Catalan chub (*S. laietanus*) (Fig. 63). Ebro barbel (*L. graellsii*) and brown trout (*S. trutta*) of the Atlantic biotype (following Aparicio et al., 2005) were the only non-native species present in this stretch.

The relative abundance of Western Mediterranean barbel varied depending on the sector and season (Fig. 64); it almost always represented more than 95% of the catch upstream of GS3 (upper section) and between GS3 and IW1 (central section). In contrast, its relative abundance is lower downstream of the irrigation weir (lower section), mainly due to the presence of Ebro barbel, which accounted for between 34% (April 2008) and 12.6% (November 2009) of the catch. Moreover, Ebro barbel appeared in the upstream section after the construction of the new fish pass in the gauging station (July 2008). Eel and brown trout presence was very low, but with stable densities in all three sectors, whereas Catalan chub appears only sporadically.

The fish crossing rates in the GS3 pool fish pass were high or moderate, associated with a high water velocity in the fourth stretch (coming from downstream) inside the fish pass (max. 2.4 m/s in June 2008 and 1.6 m/s in May 2010) and warm water (17.6°C in May 2010, 16.8°C in June 2008 and 15.1°C in October 2008), and just after high flows (>1-7 m^3/s). 3.0 Western Mediterranean barbel individuals per day were caught crossing the fish pass in June 2008 and 2.1 in June 2009 (representing 0.2% of the total migrators trapped per day in June 2008 and June 2009, and 0.7% of the total PIT tagged migrators per day in June 2009). Their presence was low in April (10.5°C in 2008 and 11.7°C in 2009) and November (12.9°C in 2009), with 0.1 and 0.2 ind./day, respectively (representing 0.01% of the total migrators trapped per day in April and 0.004% in November 2009, and 0.001% of the total PIT tagged migrators per day in November 2009).

European eel (*Anguilla anguilla*)

Brown trout (*Salmo trutta*)

Western Mediterranean barbel (*Barbus meridionalis*)

Catalan chub (*Squalius laietanus*)

Figure 63. Four native fish caught in the Llémena stream at Sant Gregori (Ter river basin; El Gironès region, Catalonia) between 2008 and 2010.

Important movements of Western Mediterranean barbel, Ebro barbel and Catalan chub were mostly associated with the spawning period (around June), and upstream migration of brown trout was also associated with its spawning period (in November).

The pool fish pass located at the gauging station permits upstream migration of the majority of fish species and individuals present downstream of the obstacle. However, medium and large Western Mediterranean barbel (FL > 0.04 m; Fig. 65 and 66), mostly females, show significant positive selection with respect to moving upstream across the fish pass. GS3 include 3 possible combined bottlenecks: excessive height of several steps (25 cm), insufficient depth of most pools (5 cm) and high water velocity.

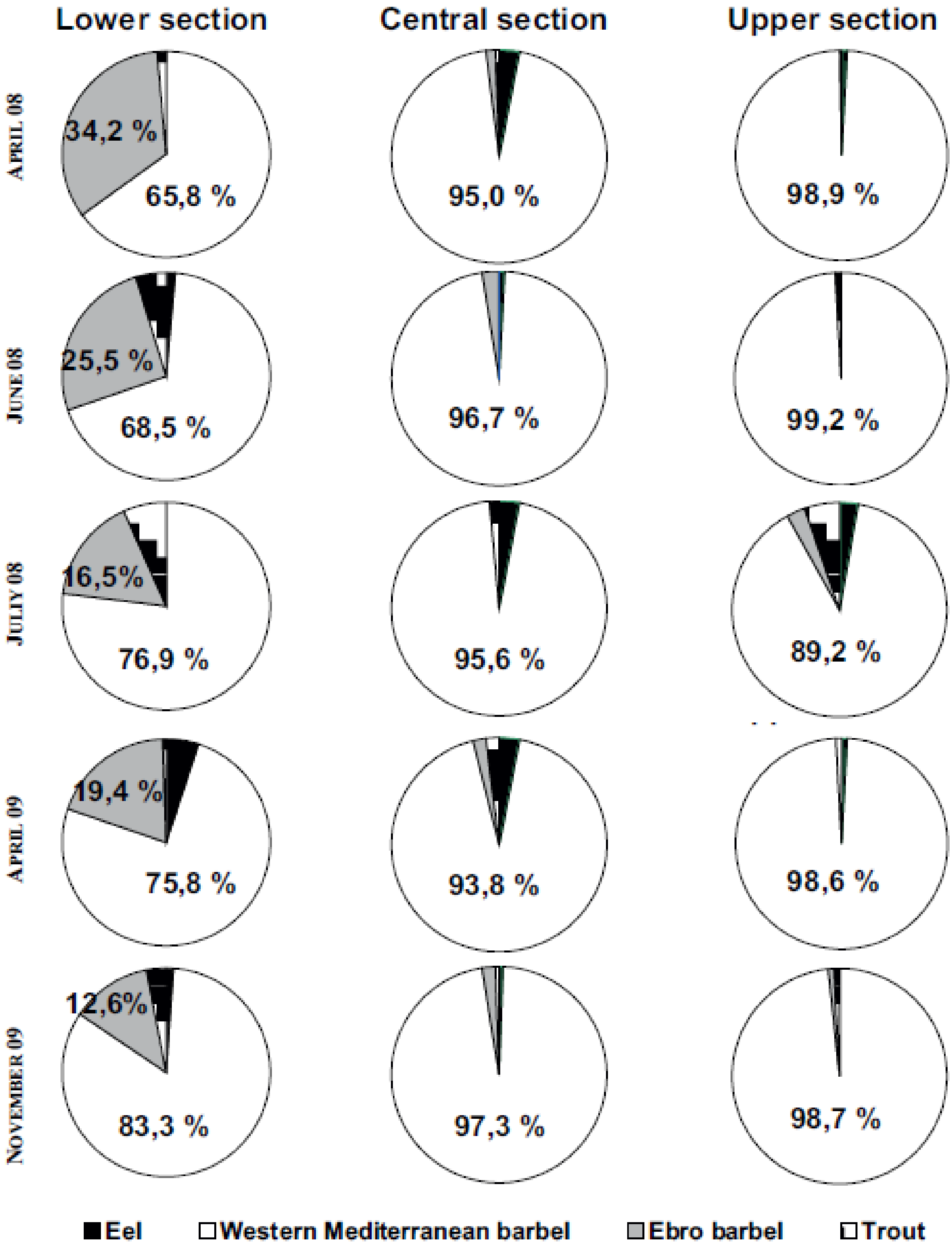


Figure 64. Fish species catch proportions upstream of the Ginestar de Llémena EA009 gauging station (GS3) (upper section) between GS3 and the Sant Gregori gardens irrigation weir (IW1) (Central section) and downstream of this irrigation weir (lower section) on the Llémena stream at Sant Gregori (Ter river basin; El Gironès region, Catalonia) during 2008 and 2009 (Ordeix *et al.*, 2011).

In addition, the IW1 weir allows a large proportion of fish to migrate upstream under any flow conditions associated with a low water velocity (Fig. 66) inside the fish ramp (max. 0.9 m/s). This obstacle (IW1) is only an important barrier for fish under conditions of very low flows (< 0.06 m^3/s).

Fish pass effectiveness at GS3 and IW1 was considered good; most fish species and individuals present downstream of these obstacles can pass in nearly any hydrological situation and fish species size frequencies downstream and upstream are similar. Thus, there are small barrier effects here.

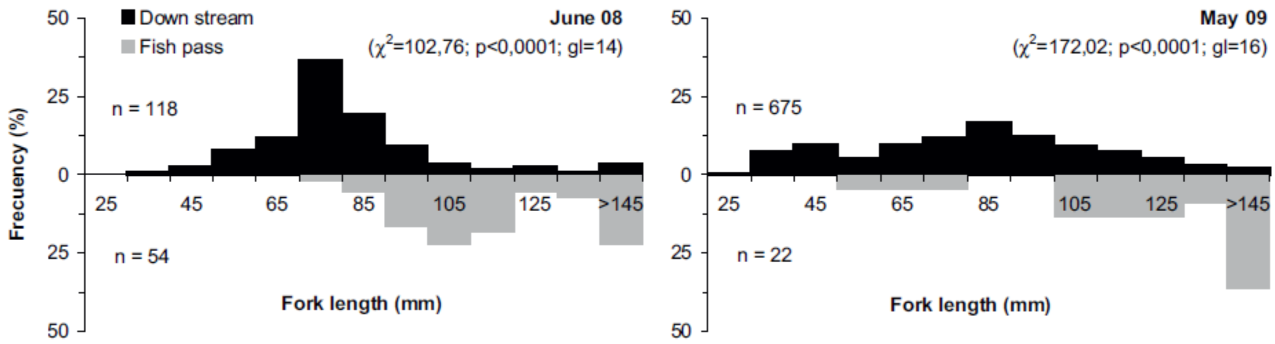


Figure 65. Western Mediterranean barbel (*B. meridionalis*) size class frequency (fork length, mm) downstream and in the water intake upstream of the fish pass of the Ginestar de Llémena EA009 gauging station (GS3) on the Llémena stream at Sant Gregori (Ter river basin; El Gironès region, Catalonia) in the spring of 2008 and 2009 (Ordeix *et al.*, 2011). Chi-square test results are also shown.

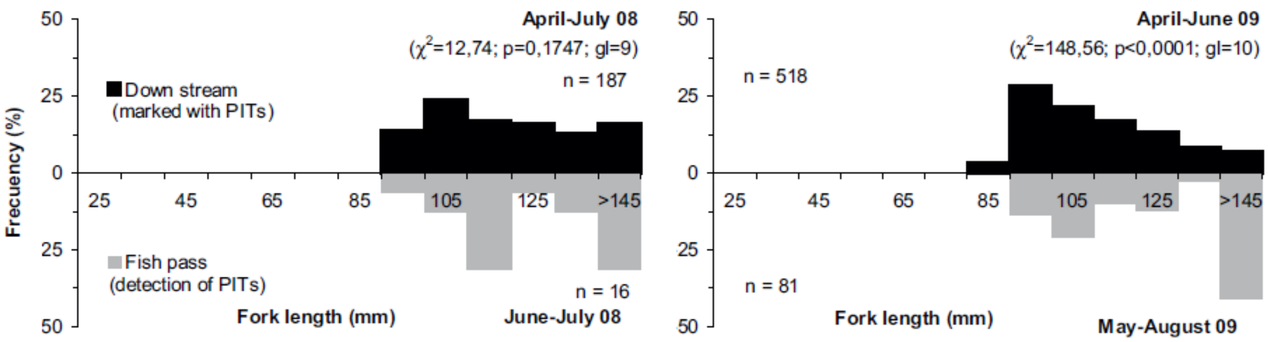


Figure 66. Western Mediterranean barbel (*B. meridionalis*) size class frequency (fork length, mm) of individuals with PIT tags detected downstream and in the water intake upstream of the fish pass of the Ginestar de Llémena EA009 gauging station (GS3) at Llémena stream in Sant Gregori (Ter river basin; El Gironès region, Catalonia) in the spring of 2008 and 2009 (Ordeix *et al.*, 2011). Chi-square test results are also shown.

8. The Llobregat river at Cal Rosal gauging station (EA066), Olvan (El Berguedà region) (GS4)

The fish community, very small and simple, consisted of brown trout (*S. trutta*), Iberian redfin barbel (*B. haasi*) and Catalan chub (*S. laietanus*) (Fig. 67). Although European eel (*A. anguilla*) potentially exist in this reach, they were not found during this study. Pyrenean minnow (*P. bigerri*) was the only alien fish species observed and the most abundant fish.

River flow suddenly rose on 14th June (from 9 m^3/s to 32 m^3/s) (see Fig. 68). The fish trap only worked correctly for the first nine days, during which great turbulence was observed downstream, apparently hindering fish swimming and jumping to the upstream side of the gauging station.

The presence of Iberian redfin barbel only downstream of the gauging station (Fig. 69) seems to be due to the persistence of small areas with gravel (without much silt), that is, a higher quality aquatic habitat than upstream, rather than due to any consideration associated with river connectivity around this obstacle.

Upstream migration rates were not considered. The data was insufficient to allow a comparison of the sizes of structures on each side of the analysed gauging station.

V-flat gauging stations have previously been associated with problems of water velocity in their central part (often higher than 3.7 m/s) and low depth (between 0.05 and 0.25 m) at the top of the obstacle, elements that limit the ability of fish to swim (Sanz-Ronda et al., 2009).

Although medium-sized and large fish of several species can probably overcome this obstacle, such as brown trout (the only species caught in the fish trap installed at the water intake upstream of this fish pass), the precarious overall settlement of the fish population on this stretch of the Llobregat River, unrelated to the existence of the gauging station, did not allow us to properly assess the level of permeability, simply due to the low density of fish.

Fish pass effectiveness at this obstacle was considered moderate: it is a partial, but important, obstacle to the free movement of fish. There is a barrier effect indicating that this fish pass might not be completely functional.

Iberian redfin barbel (*Barbus haasi*) Pyrenean minnow (*Phoxinus bigerri*)

Figure 67. Native fish (left) and non-native (right) caught in the Llobregat river at Olvan (El Berguedà region, Catalonia) in June 2010.

Figure 68. V-flat at the Llobregat river EA066 gauging station (GS4) at Olvan (El Berguedà region, Catalonia) during a flood in June 2010, negatively affecting fish pass assessment.

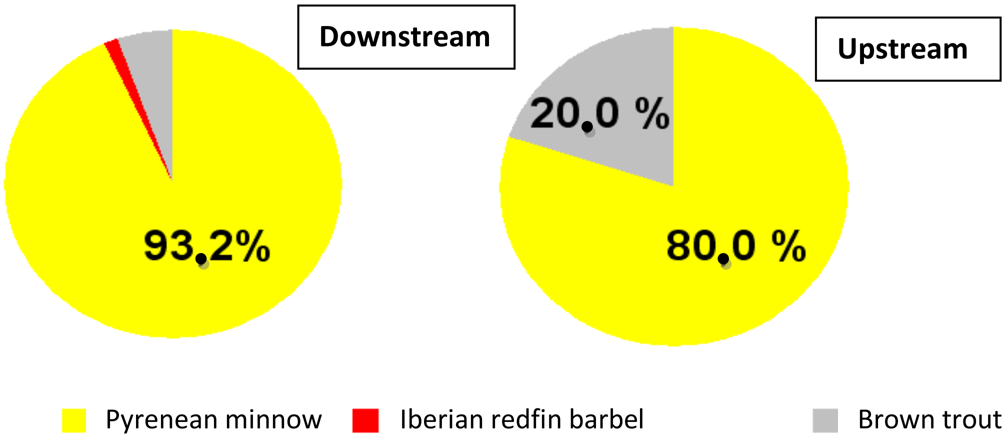


Figure 69. Proportion of catches of brown trout (*Salmo trutta*), Iberian redfin barbel (*Barbus haasi*) and Pyrenean minnow (*Phoxinus bigerri*), downstream and upstream of the V-flat at the Llobregat river EA066 gauging station (GS4) at Olvan (El Berguedà region, Catalonia) on 7th June 2010.

9. The Merlès stream (Llobregat river basin) at the Puig-reig gauging station (EA110) (El Berguedà region) (GS5)

The fish community was dominated by Iberian redfin barbel (*B. haasi*) and also included Catalan chub (*S. laietanus*) (Fig. 69). Although European eels (*A. anguilla*) potentially exist in this reach, they were not found. Rainbow trout (*Oncorhynchus mykiss*), Pyrenean gudgeon (*G. lozanoi*), Pyrenean minnow (*P. bigerri*) and pumpkinseed (*Lepomis gibbosus*) were observed alien fish species (Fig. 70).

The small differences between downstream and upstream in the proportion of catches of these species (Fig. 71) seem to be mainly related to small habitat differences. Comparing the size class frequencies of Pyrenean minnow and Iberian redfin barbel on each side of the obstacle (Fig. 72 and 73) shows the existence of significant differences, but not for the pumpkinseed (Fig. 74). Even so, the average length of these two species increases above the gauging station, a situation that can be attributed to habitat differences and not necessarily to the existence of the gauging station.

Several individual specimens of Pyrenean gudgeon, Pyrenean minnow and pumpkinseed were also caught in the fish trap upstream of the gauging station. Upstream migration rates were obtained for the Iberian redfin barbel (2.55 ind./day), the most important fish species of this river stretch. It is remarkable to observe this relatively high crossing rate in autumn, following a peak flow, when water temperature was between 7 and 10°C.

The results obtained indicate that the difficulty in overcoming this gauging station depends especially on fish size. This explains why there is a certain difference between the average length of the fish caught in the trap placed upstream of the station in comparison with the entire subpopulation in the lower section at the same time. This situation is even more evident if the size class frequencies between these two groups of fish are compared: the smaller individuals, probably recruitment of the year, do not cross the fish pass (Fig. 75).

Despite the turbulences observed at the centre of the V-flat, these did not affect swimming or jumping of native and non-native fish species upstream of the gauging station, even in a period (October and November) in which *a priori* cyprinids, which predominate on this site, are less active than in spring. This was probably related with a peak flow (3.8/s) followed by a progressive decrease over 24 days (to 0.26 m^3/s). Although water temperature was between 10.9°C and 7.3°C, most fish species and individuals moved.

Iberian redfin barbel (*Barbus haasi*)

Catalan chub (*Squalius laietanus*)

Rainbow trout (*Oncorhynchus mykiss*)

Pumpkinseed (*Lepomis gibbosus*)

Pyrenean minnow (*Phoxinus bigerri*)

Figure 70. Two native fish (top) and three non-native fish (bottom) caught in the fish trap placed at the outlet upstream of the V-flat at the gauging station on the Merlès stream (Llobregat river basin) at Puig-reig (El Berguedà region, Catalonia) in October and November 2010. Pictures: Marc Ordeix - CERM, except Catalan chub (Laia Jiménez - CERM).

Fish pass effectiveness was considered good: the results obtained, although considered preliminary, show that this fish pass is mostly permeable for all fish species, at least for a fraction of each of their populations in this river section. Fish species size frequencies downstream and upstream are similar and the majority or some of the fish groups and individuals present downstream of the obstacle can pass: there is no barrier effect, indicating that this fish pass is probably completely functional.

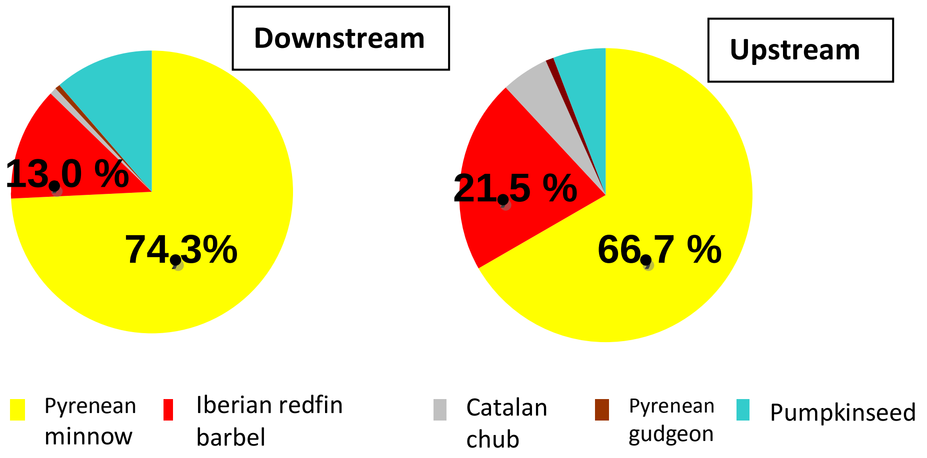


Figure 71. Proportion of catches of Pyrenean minnow (*Phoxinus bigerri*), Iberian redfin barbel (*Barbus haasi*), Catalan chub (*Squalius laietanus*), Pyrenean gudgeon (*Gobio lozanoi*) and pumpkinseed (*Lepomis gibbosus*), downstream and upstream of the V-flat at the Merlès stream EA110 gauging station (GS5) at Puig-reig (Llobregat river basin; El Berguedà region, Catalonia) on 19th October 2010. From: Ordeix et al., 2010.

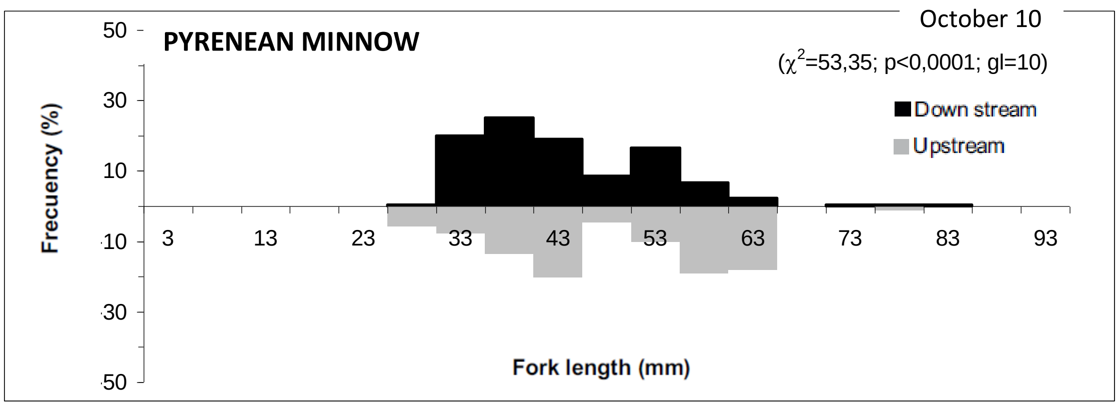


Figure 72. Pyrenean minnow (*Phoxinus bigerri*) size class frequency (fork length, mm) downstream and upstream of the V-flat at the Merlès stream EA110 gauging station (GS5) at Puig-reig (Llobregat river basin; El Berguedà region, Catalonia) on 19th October 2010. Chi-square test results are also shown.

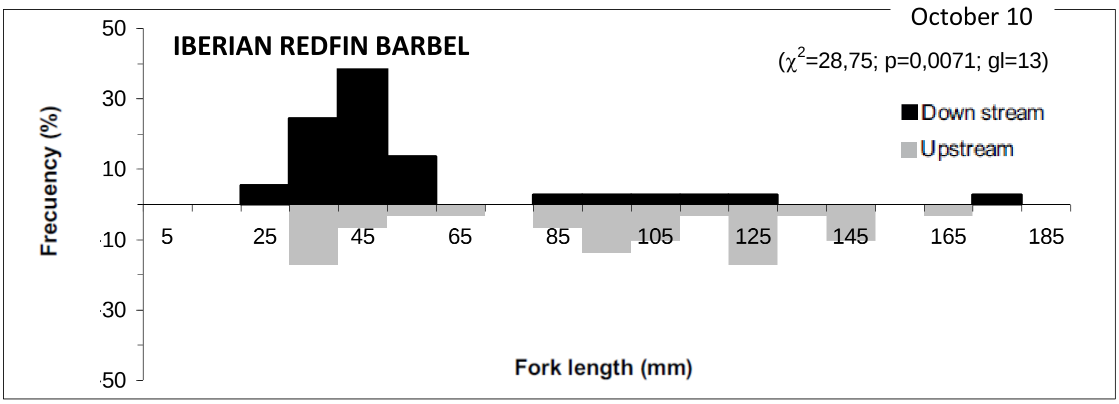


Figure 73. Iberian redfin barbel (*Barbus haasi*) size class frequency (fork length, mm) downstream and upstream of the V-flat at the Merlès stream EA110 gauging station (GS5) at Puig-reig (Llobregat river basin; El Berguedà region, Catalonia) on 19th October 2010. Chi-square test results are also shown.

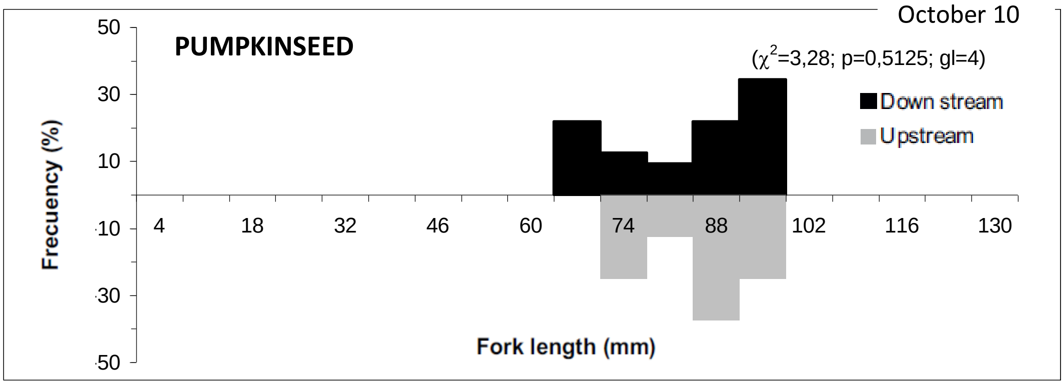


Figure 74. Pumpkinseed (*Lepomis gibbosus*) size class frequency (fork length, mm) downstream and upstream of the V-flat at the Merlès stream EA110 gauging station (GS5) at Puig-reig (Llobregat river basin; El Berguedà region, Catalonia) on 19th October 2010. Chi-square test results are also shown.

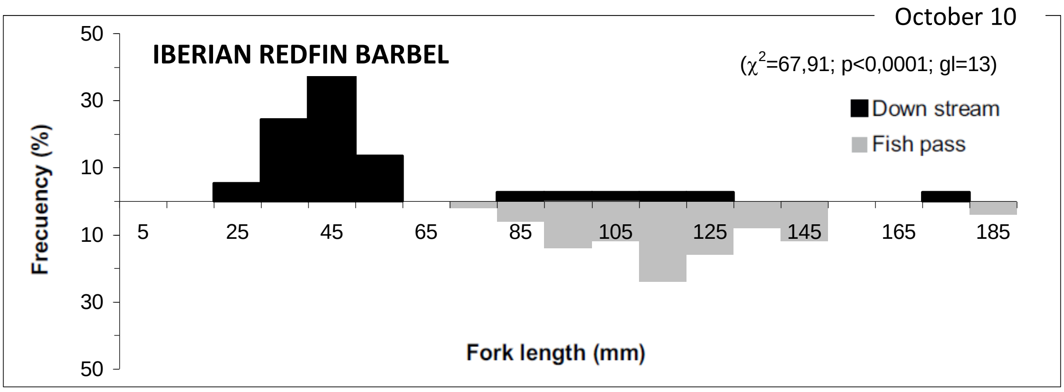


Figure 75. Iberian redfin barbel (*Barbus haasi*) size class frequency (fork length, mm) downstream and in the water intake upstream of the V-flat at the Merlès stream EA110 gauging station (GS5) at Puig-reig (Llobregat river basin; El Berguedà region, Catalonia) in October-November 2010. Chi-square test results are also shown.

10. The Ter river at La Teula hydropower weir (Manlleu, Osona region) (HPW4)

The fish community was dominated by Western Mediterranean barbel (*B. meridionalis*), Catalan chub (*S. laietanus*), and also included brown trout (*S. trutta*) and European eel (*A. anguilla*) (Fig. 76). Ebro barbel (*L. graellsii*), Pyrenean minnow (*P. bigerri*), Pyrenean stone loach (*B. guinardi*), common carp (*Cyprinus carpio*), common bleak (*Alburnus alburnus*), roach (*Rutilus rutilus*), stone moroko (*Pseudorasbora parva*) and pumpkinseed (*L. gibbosus*) were observed alien fish species.

Although certain individuals of Western Mediterranean barbel and roach started migrating in the last week of March 2002, when the water was up to 10°C, the first important peak of fish going upstream was observed during the first week in May, performed by roach (1.14 ind./day) and common carp (0.29 ind./day), following a peak flow and a certain increase of water temperature (from 11°C to 15°C). It is remarkable that the highest crossing rates were done at the end of May, when water temperature was upper to 15°C (9.00 fish/day), mainly performed by common carp (4.00 ind./day), Ebro barbel (2.75 ind./day), Pyrenean minnow (1.75 ind./day), the most important fish species on this river stretch; native species such as Western Mediterranean barbel and Catalan chub were very scarce (0.25 ind./day).

Moreover, no fish was caught migrating upstream during the assessment carried out in the last week of May 2014, probably due to low water temperatures (below 10°C) in an especially cold spring.

The size class frequencies of Western Mediterranean barbel downstream and crossing the fish pass are statistically equal, and they is a small significant difference for Catalan chub, common carp, Pyrenean minnow, roach and Ebro barbel (see Fig. 77).

The results obtained seem to indicate that the difficulty in overcoming the gauging station depends especially on fish size. Moreover, the smallest fish of several species probably are less interested in migrating in the spawning period.

Height differences observed during low flow periods in spring 2012 at the last jump of the fish ramp to arrive at the top of the weir were considered excessive (0.24-0.30 m), higher than the maximum recommended for small or medium-size cyprinid fish species in several previous assessments (0.10 m).

Western Mediterranean barbel (*Barbus meridionalis*)

European eel (*Anguilla anguilla*)

Catalan chub (*Squalius laietanus*)

Brown trout (*Salmo trutta*)

Roach (*Rutilus rutilus*)

Ebro barbel (*Luciobarbus graellsii*)

Pyrenean minnow (*Phoxinus bigerri*)

Common carp (*Cyprinus carpio*)

Figure 76. Four native fish (top) and four non-native fish (bottom) caught in the Ter river downstream of La Teula weir at Manlleu (Osona region, Catalonia) between 2010 and 2012.

Even so, fish pass effectiveness was considered good: the results obtained show that this fish pass is largely permeable for all fish species, at least for a fraction of each of their populations in this river section. Fish species size frequencies downstream and crossing the fish ramp are similar. Most or some of the fish groups and individuals present downstream of the obstacle can pass: there is no barrier effect, indicating that this fish pass is probably completely functional.

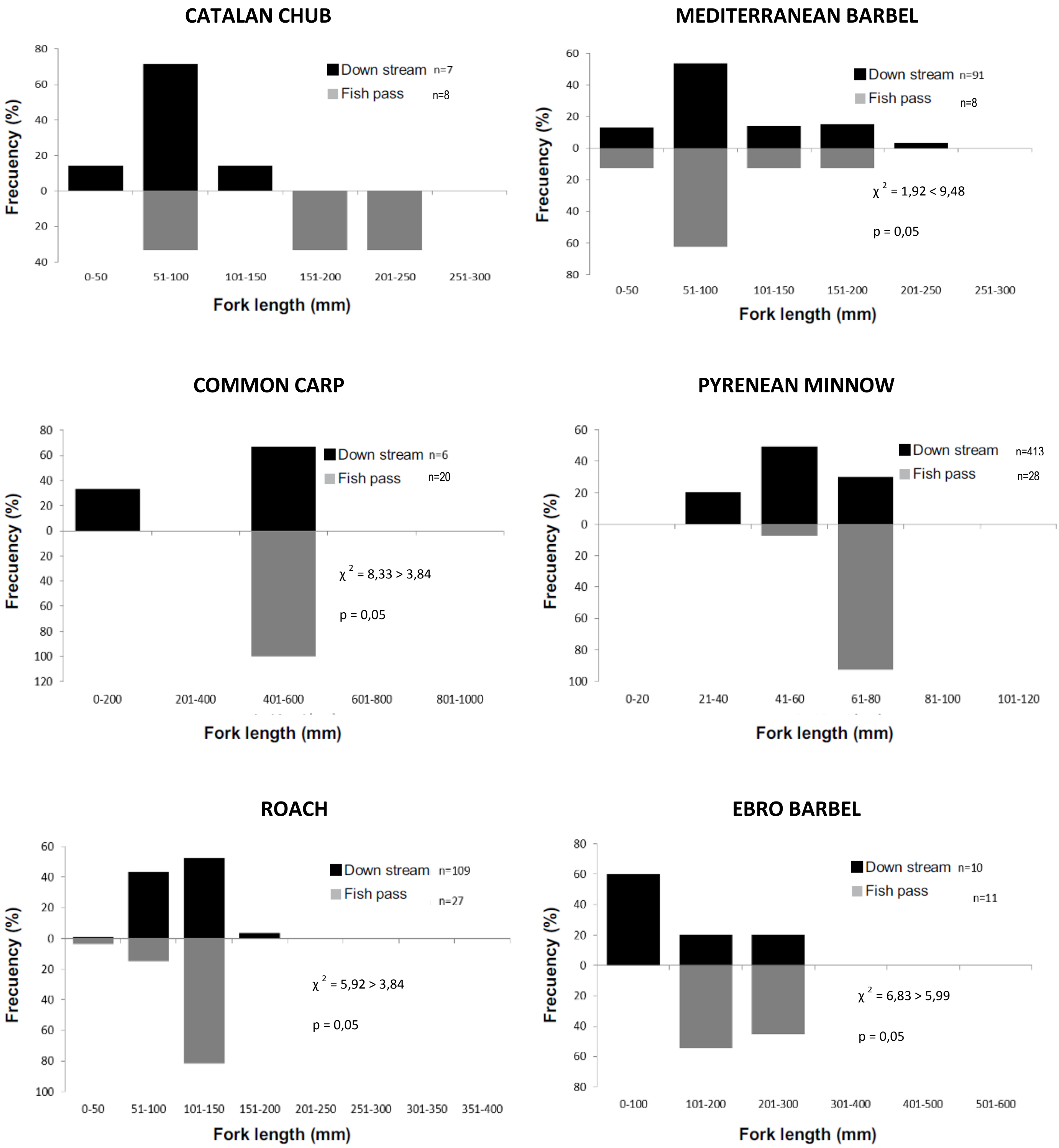


Figure 77. Western Mediterranean barbel (*Barbus meridionalis*), Catalan chub (*Squalius laietanus*), common carp (*Cyprinus carpio*), Pyrenean minnow (*Phoxinus bigerri*), roach (*Rutilus rutilus*) and Ebro barbel (*Luciobarbus graellsii*) size class frequencies (fork length, mm) downstream and in the water intake upstream of the fish ramp at the La Teula hydropower weir (HPW4) on the Ter river at Manlleu (Osona region, Catalonia) in March-May 2012. Chi-square test results are also shown.

Comparison of "in situ" fish pass effectiveness and ICF results

Observed *in situ* fish pass effectiveness agrees with the results of the ICF index (Table 12). Only a small difference is observed at the HPW2 site, where fish pass effectiveness was classified as moderate, but the result of the ICF index is poor. So, right now, fast assessment procedures agree with *in situ* fish pass effectiveness.

Table 12. Selection of fish passes on the rivers of Catalonia for evaluating fish pass effectiveness. The most important characteristics, including obstacle and pass types, monitoring techniques, *in situ* fish pass effectiveness (FPE), ICF index results (Solà *et al.*, 2011) and differences between FPE and ICF (1 = Natural conditions, 2 = Good, 3 = Moderate, 4 = Poor and 5 = Bad).

Code	**River name**	**Obstacle type**	**Fish pass type**	**Fish pass description**	***In situ* FPE**	**ICF index**	**FPE-ICF**
HPW1	Ter	Hydropower weir	Broad-spectrum technical solution	Pool fish pass without drops	3	3	0
GS1	Ter	Gauging station	Broad-spectrum technical solution	Pool fish pass	3	3	0
HPW2	Segre	Hydropower weir	Broad-spectrum technical solution	Pool fish pass	3	4	-1
HPW3	Querol	Hydropower weir	Broad-spectrum technical solution	Deflectors	2	2	0
GS2	Tordera	Gauging station	Close-to-nature	Fish ramp	3	3	0
GS3	Llémena	Gauging station	Broad-spectrum technical solution	Pool fish pass	2	2	0
IW1	Llémena	Irrigation weir	Close-to-nature	Fish ramp	2	2	0
GS4	Llobregat	Gauging station	Broad-spectrum technical solution	Smooth ramp (V-flat)	3	3	0
GS5	Merlès	Gauging station	Broad-spectrum technical solution	Smooth ramp (V-flat)	2	2	0
HPW4	Ter	Hydropower weir	Close-to-nature	Fish ramp	2	2	0
Differences:							**-1**

6.4. Discussion

Until 2010, 95 fish passes were identified and underwent a preliminary assessment. There were fish passes at 11% of main river obstacles to fish migration in the rivers of Catalonia.

There were few examples of dam and weir removal and close-to-nature fish passes, in contrast, for example, to other areas of the Iberian Peninsula, such as the Basque Country and Navarra, and the Duero river basin, where there were already many (Brufao, 2006).

Fish passes identified were typically retro-fitted solutions using broad-spectrum technical structures, mainly pool-type fishway or pool fish pass facilities. Most of them were mainly in the Pyrenees to improve brown trout (*S. trutta*) fisheries (90%). Only partially (37% of total) were reliable fish passes for all native fish in Catalan rivers, classified with good or very good connectivity (following the ICF index). Apart from this, fish passes have been little used in Catalonia, without the necessary coordination to improve fish migration at entire watershed scale, especially to recover, for example, the European eel (*A. anguilla*) from sea to source.

Detailed analyses of solutions used in Catalonia to improve fish migration showed that fish passes were scarce, and where they do exist, they were poorly maintained, or insufficient for all of the native fish fauna in each water body. With some exceptions, fish passage rates were quite low; only those species with great ability to overcome obstacles, such as salmonids, or larger individuals of other fish groups were able to migrate.

The situation was quite similar, for example, in Australia in 1985, when there were only 44 fish passes for the thousand obstacles throughout the country, most of which were poorly maintained and generally inoperable for all native fish species (Thorncraft & Harris, 2000). There was a similar situation in European countries, such as France (Larinier, 2001; Larinier, 2002e), where the experience gained shows that the most frequent causes of malfunctioning of fishways are poor performance resulting from inadequate maintenance and lack of attractivity of the facilities, the UK (Armstrong et al., 2004) and the Netherlands (Kroes et al., 2006) until the 1990s.

The ICF index (Solà *et al*., 2011) was tested for 10 fish passes in the rivers of Catalonia, obtaining results that are coherent with the real permeability of the obstacles. The good coincidence of ICF index results with fish pass effectiveness estimation for the ten fish passes studied is not surprising, as the ICF integrates fish pass effectiveness criteria described in this study. Although the results of the ICF index are consistent, they come from a relatively small number of cases (10 until 2012). Therefore, it is necessary to replicate this study at additional fish passes to validate these results. However, the most reliable way to verify the effectiveness of a fishway is the estimation of rate of fish passage, which is defined as the amount of fish per unit of time that can ascend the barrier through the fish pass (Travade & Larinier, 2002; Marmulla & Welcomme, 2002; Roni, 2005).

The ease of application of the ICF index compared to *in situ* measurements of fish movements and the detailed information recorded by the index make it a very useful tool for the diagnosis of the longitudinal connectivity of rivers and for guiding measures for hydromorphological quality improvement. In addition, due to the variety of species and hydrological regimes addressed and solutions used to date, it is essential to complement this quick assessment technique with the determination of the *in situ* fish pass effectiveness of any new solution implemented.

Regarding the independent results obtained for each of the 10 assessed fish passes, it is important to note that HPW1 is a vertical slot fish pass without drops. Vertical slot fish passes are particularly well suited to sites where upstream and/or downstream water level fluctuations are significant (Larinier, 2002e), as in this case. However, HPW1 had a clear barrier effect for YOY trout and for young and adult Western Mediterranean barbel. However, this was not sufficient to produce clear differentiation in upstream and downstream population size structures. Moreover, ongoing migration of only larger barbels (basically females) could cause reproduction and isolation problems for this species and greatly reduce its population abundance in this river (Thorncraft & Harris, 2000; Lucas & Baras, 2001). The main constraint in this case seemed to be high water velocity between pools (>2 m/s) and low pool depths (< 0.01 m).

Moreover, GS1 was assumed to exert a clear barrier effect for mullets (*M. cephalus* and *L. ramada*) and Ebro barbel (*L. graellsi*) and probably for other species present. In this case, the main problem was associated with the existence of traverses 0.25 m in height and some of 0.6 m, which was passable only for large individuals and thus represents an impermeable obstacle. However, this obstacle might be permeable to some glass eel individuals migrating through the bridge base, and freshwater blenny (*S. fluviatilis*) might also be able to cross upstream (Travade & Larinier, 2002d; Marmulla & Welcomme, 2002). This mostly agrees with an evaluation of the upstream passage performance of the Iberian barbel (*Luciobarbus bocagei*) when encountering small weirs, combining different plunge pool depths with different waterfall heights carried out in an indoor channel (Amaral et al., 2016). Both shallow plunge pool depths and high waterfall heights may restrict the successful passage of Iberian barbel. Even though successful passage of small instream obstacles seems to be a complex phenomenon, the combination of plunge pool depths of 20 cm (in a range of 10-50 cm) and waterfall heights of 10 cm (in a range of 5-25 cm) provided the best results.

In contrast, the HPW2 traverses were only 0.1 m high, and the water velocity at this site was generally less than 0.5 m/s. These conditions were quite appropriate for most of the fish present to cross. However, the fish pass was only 0.75 m wide, while the weir is 70 m wide, and the flow through the fish pass (when water flows through the fish pass are > 0.03 m^3/s) was extremely low in relation to river flows (0.3-9.0 m^3/s between 07/04/12 and 07/11/07). All of these conditions have been shown to limit fish crossing rates elsewhere (Larinier, 2002a; Larinier, 2002b; Larinier, 2002c; Larinier *et al.*, 1994; Marmulla & Welcomme, 2002; Armstrong *et al.*, 2010; Gough *et al.*, 2010).

HPW3 only produced a large barrier effect in low flow conditions, when the low water level (max. 0.2 m) in the deflector does not allow brown trout passage upstream and quite likely also prevents the passage of the other two native fish species.

In contrast, fish passage rates at GS2 were low but similar to those observed for small cyprinids at other fish passes in Catalan rivers (HPW2, GS3 and IW1) during the same study period. It is worth noting that glass eels were observed in May climbing a vertical (90°) wall of concrete but failing to reach the top of the barrier because it was covered by a steel beam with overhanging material. This finding represents a major problem for the migration of glass eels and has also been documented in other studies (Larinier, 2002d; Armstrong *et al*., 2010).

Deficiencies in the design of the fish pass at GS3 included insufficient pool depth, excessive height over the first jump (although this was improved in 2009) and a current velocity that is too high for the majority of cyprinid species (often > 2 m/s). However, these deficiencies only seem to affect smaller Western Mediterranean barbel individuals. Likewise, IW1 is assumed to represent an obstacle to colonising upstream areas for Ebro barbel, and the first appearance of this species in upstream sections might be related to the construction of the new fish pass at the gauging station (July 2008).

Pending a complete assessment, the V-flat (such as GS5) seems to be a good solution to improve fish migration at gauging stations in streams and small tributaries.

Close-to-nature fish passes assessment is mostly pending for Catalan rivers. However, information is already available, and positive, for a fish ramp (HPW4) at La Teula hydropower weir on the Ter river at Manlleu (Osona region) and the associated fish ramps at the gauging stations on the Fluvià at Olot (La Garrotxa region) and the Muga river at Boadella d'Empordà (L'Alt Empordà region). At HPW4, fish species size frequencies downstream and crossing are similar, implying a small barrier effect and good fish pass effectiveness. These three fish ramps had high values on the ICF index (85, 95 and 95, respectively).

Proposals to improve river connectivity for fish in Catalonia

In summary, regarding fish passes existing in Catalonia until 2010, most of them broad-spectrum technical structures, assessment indicates that brown trout (*S. trutta*), which exhibit a high capacity to overcome obstacles by swimming and/or jumping (Larinier *et* *al*., 1994; Armstrong *et al*., 2010), seem to be able to migrate upstream using the different types of fish passes constructed in Catalonia.

However, the results obtained show that if fish pass waterfalls are higher than 0.2 m and/or fish pass water velocity is higher than 2 m/s, only the largest individuals of species with great ability to overcome obstacles, such as brown trout, or moderate ability, including mullets (*L. ramada*, *M. cephalus* and *C. labrosus*) and some cyprinid species, such as Ebro barbel (*L. graellsii*; FL >0.55 m), Western Mediterranean barbel (*B. meridionalis*; FL >0.13 m), Iberian redfin barbel (*B. haasi*) and Catalan chub (*S. laietanus*), are able to cross upstream.

Moreover, if a fish pass waterfall has a maximum height of 0.1 m and/or a water velocity of less than 0.5 m/s, the results show that most species and individuals can use the fish pass, including small species with a low capacity to overcome obstacles, such as Pyrenean gudgeon (*G. lozanoi*), Pyrenean minnow (*P. bigerri*), European eel (*A. anguilla*), and YOY of other species including brown trout (*S. trutta*), Ebro barbel (*L. graellsii*) and Western Mediterranean barbel (*B. meridionalis*; FL< 0.09 m).

In addition, with regard to the fish passes assessed and reference authors (Larinier, 2002a; Larinier, 2002b; Larinier, 2002c; Larinier et al., 1994; Marmulla & Welcomme, 2002; Gough et al., 2006; Armstrong et al., 2010), it is also important to take into account all potentially present native species and boost several conditions in their favour (unfortunately infrequently observed) such as:

a) if there is a waterfall, the fish pass entrance from downstream must have a maximum height of 0.2 metres, as well as controlling undermining;

b) avoid turbulence into the fish pass;

c) the width of the fish pass should be greater than one twentieth of the total width of the river;

d) always ensure regular maintenance and monitoring of the fish passes;

e) the input downstream must be as near as possible to the obstacle;

f) it is necessary everywhere to include mechanisms preventing fish from going into turbines or channels;

g) create and keep a deep pond (minimum of 0.60 m, but preferably deeper) to jump from downstream to the fish pass entry;

h) design deep pools (minimum of 0.10 m, but preferably deeper) in the fish passes;

i) water flow must attract fish to the entrance and must flow through the fish pass; e.g. flow of the fish pass must be equal or greater than the defined environmental flows for each river stretch.

Important movements of fish were mostly associated with particular spawning periods and/or periods just after high or moderate peak flows, as has been indicated in many other studies (Reiser & Peacock, 1985; Larinier *et al.*, 1994; Lucas & Baras, 2001; Marmulla & Welcomme, 2002). This finding also supports the idea that fish pass evaluation should be performed particularly at times of maximum activity of different fish species. This has been shown by the high upstream migration rates obtained for the Iberian redfin barbel (*Barbus haasi*) at the Merlès stream (GS5) in autumn, when water temperature was between 7 and 10°C, following a peak flow. It was not previously observed in a similar species, Western Mediterranean barbel (*Barbus meridionalis*), in other assessed fish passes in Catalonia (HPW1 and GS3), probably because the most important monitoring effort was in spring and summer (associated with cyprinid spawning period).

It is important to restore connectivity for at least a thousand obstacles in Catalonia if a good ecological status is to be achieved, and in the light of the present results, if dam or weir removal is not possible, multispecies fishways are recommended in most locations.

A restoration programme should consider the preferred option of dam and weir removal or, where necessary, the construction of close-to-nature devices, such as fish ramps, rock ramps, by-pass channels or streams. They provide optimal conditions for a wider range of species, individuals and river flows (Marmulla & Welcomme, 2002). Their maintenance is simplest.

In exceptional sites, broad-spectrum technical solutions can be used, such as pool fish passes with vertical slots, low waterfalls and low water velocities, involving a range of less optimal conditions and more investment in maintenance (Marmulla & Welcomme, 2002). Their establishment at large reservoirs should also be considered.

All solutions regarding fish passages should be established based on criteria of effectiveness and with the participation of experts on fish and river connectivity during the design and construction processes.

Finally, the mobility of native fish fauna, including their capacity to use upstream fish passes or negotiate artificial barriers to fish passage and their natural patterns of movement, especially in Mediterranean rivers, is still poorly understood (Jungwirth *et al.*, 1998; Marmulla & Welcomme, 2002; Gough *et al.*, 2012). Thus, additional research on these issues for all native species is urgently required.

Moreover, fish pass projects could provide insight into fish movement patterns. However, these projects often do not have sufficient resources for adequate assessment of fish pass effectiveness, and they provide patchy knowledge regarding fish movement patterns (Lucas & Baras, 2001; Roni, 2005). Advancing our understanding of fish movement patterns will require regularly monitoring the effectiveness of the principle fish migration solutions, especially in large rivers because of their importance for anadromous and catadromous fish species.

For fishways situated in key locations, for example, in the lower parts of rivers, it would be appropriate to adapt fish pass structures to enable the installation of large permanent fish traps, as has been performed in many European countries, especially those that have large salmon or eel fisheries (Reddin *et al.*, 1992; Eatherley *et al.*, 2005; Gough *et al.*, 2012), or automatic fish counting devices (e.g. based on electric resistivity, infrared light and/or an additional video camera system; Dunkley *et al.*, 1992; Thorley *et al.*, 2005; DEFRA, 2010).

6.5. Conclusions

The results have shown that:

a) Ecological connectivity for fish in Catalan rivers is bad. Very few examples of weir and dam removal exist and only 95 (11%) of river obstacles include fish passes.

b) River connectivity has been little developed, without the necessary coordination to improve fish migration at entire watershed scale, for example to recover the European eel (*A. anguilla*) from sea to source.

c) Less than half of fish passes (39%) resulted in an ICF index value of good or very good. Usually fish passes do not adequately address the requirements of native fish species: they are generally badly designed or poorly maintained (61% of existing solutions).

d) The most serious problems of fish passes in the rivers of Catalonia in 2010 were:

   A. Insufficient size of the fish pass (28.4%).
   B. Absence or poor flow at the fish pass entrance (13.7%).
   C. Over-shallow pond for jumping from downstream to the fish pass entry (19.0%).
   D. Entrance located too far from the obstacle (24.2%).
   E. Waterfall too high at the fish pass entrance from downstream, mostly produced by undermining (48.4%).
   F. Excessive height between adjacent pools (24.2%).
   G. Excessive speed into the fish pass (35.8%).
   H. Too much turbulence in the fish pass (34.7%).
   I. Shallow pools in the fish pass (21.1%).
   J. Obstruction, filling or structural disrepair of the fish pass, due to lack of maintenance (28.4%).
   K. Absence of mechanisms to prevent fish from going into turbines or bypass channels (24.2%).

e) Fish pass crossing rates of the apparently suitable fish passes of Catalonia, with few exceptions, are low; only those species with great ability to overcome obstacles, such as salmonid, or larger individuals of other fish groups, often predominantly female cyprinids, are able to migrate. In many cases only the upstream movements of larger fish are facilitated.

f) Pending a complete assessment, the V-flat seems to be a good solution to improve fish migration at gauging stations on streams and small tributaries.

g) Close-to-nature fish passes implementation projects and their assessments are for the most part pending for Catalan rivers.

h) Although the results of implementing the ICF index and *in situ* assessments at 10 fish passes are quite consistent, it is necessary to assess more fish passes, and validate or improve these methods.

i) Regarding assessed fish passes and reference authors, several proposals to improve river connectivity for fish in Catalonia are:

   A. A fish pass waterfall must to include a maximum height of 0.1 m and/or a water velocity of less than 0.5 m/s.
   B. The fish pass entrance from downstream must have a maximum height of 0.2 metres, as well as controlling undermining.
   C. Avoid turbulence into the fish pass.
   D. The width of the fish pass should be greater than one twentieth of the total width of the river.
   E. Always ensure regular maintenance and monitoring of the fish passes.
   F. The entrance downstream must be as near as possible to the obstacle.
   G. It is necessary everywhere to include mechanisms for preventing fish from going into turbines or channels.
   H. Create and keep a deep pond (minimum of 0.60 m, but preferably deeper) to jump from downstream to the fish pass entry.
   I. Design deep pools (minimum of 0.10 m, but preferably deeper) in the fish passes.
   J. Water must attract fish to the entrance and must flow through the fish pass; e.g. flow of the fish pass must be equal or greater than the defined environmental flows for each river stretch.

j) We still need better knowledge of migratory behaviour for most native Iberian freshwater fish species crossing fish passes, especially those with less socio-economic interest (but no less interest biologically and ecologically), and downstream migration for all species.

k) Due to the high variability in jumping and swimming capabilities of native fish species, and the great diversity of river types in our river basins, it is essential to carefully assess each new pass that is implemented, particularly during the spawning periods of potentially present native fish species, but not only then. Moreover, fish pass assessment could also provide insight into fish movement patterns.

l) For fishways placed in key locations, for example, in the lower parts of rivers, it would be appropriate to adapt fish pass structures to enable the installation of large permanent fish traps, especially those that have important salmon or eel fisheries, and automatic fish counting devices.

7. Fish migration and fish ramp assessment at a gauging station on the Fluvià river at Olot (NE Catalonia)

7.1. Introduction

Currently, most fish can no longer migrate to complete their life cycle in Catalonia, Europe and most of the world because their natural habitats have been modified by human activity. River obstacles cause direct effects on population biology, such as local extinctions due to a lack of dispersion and recolonisation, genetic isolation, non-accessibility to spawning or feeding areas, refuges from predators and shelter areas for harmful environmental conditions, i.e. pollution, big floods, droughts or other human disturbances and natural disasters (Lucas & Baras, 2001). Existence of rivers with poor connectivity is considered a main cause of decline for many fish species in inland waters in the Iberian Peninsula (Doadrio, 2001; Santo, 2005), Europe (Bruslé & Quignard, 2001; Larinier, 2002a) and worldwide (Gough *et al.*, 2012).

Reestablishment of river connectivity became a legal requirement under the Water Framework Directive (2000/60/EC) and the European Plan for Eel Recovery (Regulation 1100/2007). It is also considered extremely important for the conservation of endangered freshwater species included in the Habitats Directive (92/43/CEE). However, the capacity of native fish fauna to use fish passes and their natural patterns of movement are still poorly understood (Marmulla & Welcomme, 2002). Moreover, fish pass assessments could provide important knowledge regarding fish movement patterns (Lucas & Baras, 2001; Roni, 2005).

Restoration of fish migration should pay proper attention to dam and weir removal, which is the most environmentally positive solution in the medium and long term (Gough *et al.*, 2012). If the cultural value of the obstacle or its current use (hydropower, irrigation, etc.) do not allow for removal, the promotion of close-to-nature fish passes, such as lateral channels and fish ramps, which provide optimum conditions for a wider range of species, individuals and flows (Marmulla & Welcomme, 2002), should be carried out.

Close-to-nature device assessment in Catalan rivers is mostly still pending (with the exception of the fish ramp of the Ter river at Manlleu). Hence the interest in the fish ramp associated to the gauging station on the Fluvià river at Olot (EA013), renovated in 2010, which follows international guidelines for fish passes and, especially, for fish ramps (Gebler, 1998; Larinier, 2002d; Marmulla & Welcomme, 2002).

The aims of this study were (1) to assess effectiveness of the fish ramp of the Fluvià river (Mediterranean) during the cyprinid reproductive period, at other times and under different environmental conditions; (2) to improve knowledge on main causes and capabilities for migration of several Mediterranean freshwater fish.

7.2. Methods

Study area

The Fluvià river rises at an altitude of 1175 metres in the Garrotxa region (NE Catalonia). It runs 99.5 km before flowing into the Mediterranean Sea, with a discharge of 264.41 Hm^3/year (Catalan Water Agency database). Its basin does not include large dams (> 10 m high). However, there is a total of 117 facilities involving some kind of barrier for fish migration (Ferrer *et al.*, 2009). The region's climate is Mediterranean mountainous, with annual rainfall ranges of 850-1100 mm. Winter is cold, with average temperatures from 4°C to 7°C, and summer warm, between 17°C and 22°C (database of the Meteorological Service of Catalonia). Forest dominates the landscape, but extensive open ground (especially with corn) is also abundant.

The gauging station EA013 on the Fluvià river is located at an altitude of 398 m, 23 km from the river source, downstream from the town of Olot, in the Volcanic Area of the Garrotxa Natural Park (Fig. 78-90). There, the Fluvià river discharges 47.38 Hm^3/year and has an average flow of 0.71 m^3/s (range: 0.19-1.32 m^3/s for the last 10 years) (Catalan Water Agency database).

This gauging station is 18.0 m width, including a low-water channel of 5.5 m width and 0.3 m height, and a close-to-nature fish pass, a fish ramp of 1.0 m wide, 11.0 m long and with a 10% slope (Fig. 80). Imitating natural substrate, stones were scattered along the ramp bottom. The weir includes an overhanging structure on top. The fish ramp entrance location (from downstream to upstream) is as close as possible to the weir.

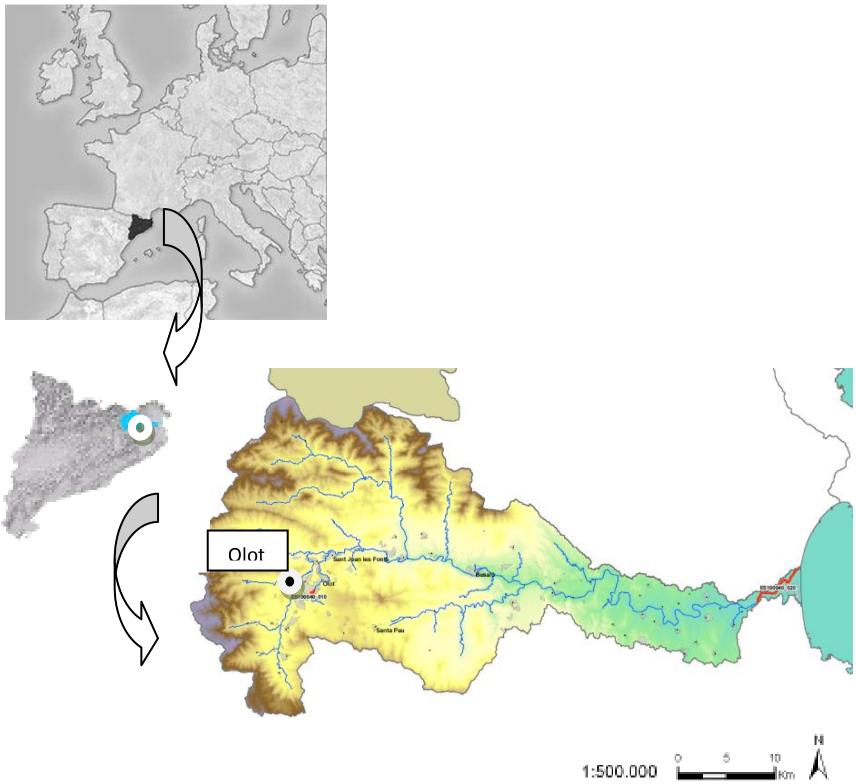


Figure 78. Study site (black dot) in the Fluvià river at Olot (NE Catalonia, NE Iberian Peninsula).

Figure 79. The Fluvià river 100 m upstream (left) and 100 m downstream (right) of the gauging station EA013 of the Catalan Water Agency at Olot (La Garrotxa region, NE Catalonia) in October 2013.

General data collection

The assessment of barrier effects and fish migration was undertaken in two periods: (1) 29th April to 27th May 2013, during the expected spawning period and high migration activity of cyprinids (Sostoa et al., 1990; Doadrio, 2001); and (2) 5th October to 2nd November 2013, in order to collect information on fish movements out of their spawning period.

Fish pass effectiveness was assessed following useful previous criteria for Mediterranean rivers (Santos *et al.*, 2006; Ordeix *et al.*, 2011): (1) General data collection; (2) Indirect estimation techniques, using trapping fishing systems to compare fish population structure 100 m above and 100 m below the fish pass; and (3) Direct estimation techniques, installing a fish trap at the water intake upstream of the fish ramp (Fig. 81) to compare fish population structure and fish crossing rates with potentially migrating downstream fish population, obtained by using electrofishing systems (depletion sampling; Zippin, 1958) in the river stretch of 100 m located immediately downstream of the gauging station, complemented by a daily collection of hydrological and environmental data.

River habitat and riparian vegetation indexes, IHF (Pardo *et al.*, 2002), RBPs (Plafkin *et al.*, 1989; Barbour *et al.*, 2002) and QBR (Munné *et al*, 1998) were preliminarily obtained 100 m upstream and 100 m downstream the obstacle (Fig. 79). Daily physicochemical parameters (water temperature, electric conductivity, pH and dissolved oxygen) were calculated by using a multiparametric YSI Professional portable probe. Daily average river flow was reported by the Catalan Water Agency. Several physical variables were measured daily at this hydraulic device, including velocity by using a Global Water FP101 flow meter, operating levels of the fish pass, and water depths and waterfall heights at the gauging station and at 7 sections of the fish ramp (in order to obtain medium and minimum values at each). To assess the theoretical degree of impediment for fish passage, the ICF index (River Connectivity Index; Solà *et al.*, 2011) was also calculated.

Indirect estimation techniques

Indirect estimation techniques used in this study consisted of a comparison of current fish populations 100 m upstream and 100 m downstream the obstacle (Fig. 79; Santos *et al*., 2006) by fish trapping systems (Travade & Larinier, 2002; Roni, 2005) using two kinds of fish traps without bait: *camaronera* (2 m long, 0.006 m mesh size) and *anguilera* (3.5 m long, 0.010 m mesh size) (Clavero *et al.*, 2006). Species composition and parameters such as size structure allowed the characterisation of fish populations. The fish trapping campaign was performed in October: at New Moon and Full Moon.

Figure 80. Gauging station EA013 of the Catalan Water Agency on the Fluvià river at Olot (La Garrotxa region, Catalonia) in May 2013.

Figure 81. Fish trap installed at the water intake upstream of the fish ramp of the gauging station EA013 of the Catalan Water Agency of the Fluvià River at Olot (La Garrotxa region, Catalonia) in May 2013.

Direct estimation techniques

A barrier effect was also deduced by comparing fish population downstream (obtained by depletion sampling) and captured fish at the water intake of the fish pass, migrating, mainly using fish crossing rates and deviations of size frequencies (Lucas & Baras, 2001; Roni, 2005). Electrofishing procedures (CEN standard norm *UNE-EN 14011:2003*), using Erreka III equipment with a Honda GXV50 motor (220V, 50Hz and 2,200W), were employed to sample fish population downstream. A cross-section of the fish pass was completely blocked off during two periods (May and October) using a fish trap 4.5 m long with 0.010 m mesh size, with a tight connection to the bottom.

Statistical analysis

Deviations in the most abundant fish species size frequencies 100 m downstream and 100 m upstream of the obstacle, and downstream and crossing the water intake upstream of the fish pass, were analysed by means of a Chi-square test. The mean sizes of fish between campaigns were also analysed by means of a Chi-square test. In both cases, the statistical package *R version 2.15.0* (2012-03-30; R Development Core Team, 2012) was used.

7.3. Results

Fish community

The fish community downstream the gauging station consisted of 4 species in spring, an estimated density of 6720 individuals per hectare (ha) and a total biomass of 159 kg per ha (obtained by depletion sampling). Two native species (Fig. 82) were common: Western Mediterranean barbel (*Barbus meridionalis*) (estimated downstream: 4614 ind./ha, 42.69 kg/ha, mean size: 0.81 m (range: 0.019-0.187), mean weight: 16 g (range: 2-62)) and Catalan chub (*Squalius laietanus*) (estimated downstream: 896 ind./ha, 21.65 kg/ha, mean size: 0.103 m (range: 0.019-0.202), mean weight: 38.1 g (range: 2-111)). Two non-native species were also present: Pyrenean minnow (*Phoxinus bigerri*) (estimated downstream: 1165 ind./ha, 1.32 kg/ha, mean size: 0.038 m (range: 0.021-0.068), mean weight: 1.13 g (range: 1.20-3.70)) and common carp (*Cyprinus carpio*) (estimated downstream: 45 ind./ha, 93.35 kg/ha, mean size: 0.462 m (range: 0.444-0.480), mean weight: 2084 g (range: 1790-2378)). The fish community consisted of the same 4 species in autumn.

The average somatic condition (FL-TW relationship) of Western Mediterranean barbel (*B. meridionalis*) was 5.03 mm/g in spring and 4.45 in early autumn; for Catalan chub (*S. laietanus*) it was 2.69 mm/g in spring and 2.53 in autumn; for Pyrenean minnow (*P. bigerri*) it was 33.25 mm/g in spring and 17.72 in autumn; and for common carp (*C. carpio*) it was 0.21 mm/g in spring.

Based on visual observations, Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*Squalius laietanus*) spawning period was, at least, between 10th May and 15th July. This information was not available for Pyrenean minnow (*P. bigerri*) and common carp (*C. carpio*).

Figure 82. Western Mediterranean barbel (*Barbus meridionalis*) (left) and Catalan chub (*Squalius laietanus*) (right) captured just after crossing the fish ramp at the gauging station EA013 of the Catalan Water Agency on the Fluvià river at Olot (La Garrotxa region, Catalonia) in May 2013.

Environmental data

River habitat was diverse and with very good quality both 100 m downstream and 100 m upstream the gauging station, following the IHF (score of 93, downstream and upstream) and RBPs (score of 176, downstream and upstream) indexes. On the river bed, blocks, stones and gravel were predominant. The riparian vegetation was mainly alder (*Alnus glutinosa*) and ash tree (*Fraxinus excelsior*) (Fig. 79), with good quality following the QBR index (score of 90 downstream and score of 100 upstream).

Mean water flow (1.290 m^3/s), pH (8.4) and dissolved oxygen (11.85 mg/l) were higher and water temperature was lower (12.8°C) in spring. Mean water flow was much lower (0.161 m^3/s), pH (7.9) and dissolved oxygen (8.98 mg/l) were lower and water temperature was higher (14.6°C) in autumn. Electrical conductivity was similar (520 µS/cm in spring and 568 µS/cm in autumn). Environmental parameters collected and indexes calculated are shown in Tables 13-14.

Table 13. Environmental data of the Fluvià river (100 m upstream and 100 m downstream the obstacle) and fish ramp at the gauging station (EA013) at Olot (NE Catalonia), during the two study periods of 2013.

Study period		**IHF index** (Pardo *et al.*, 2002)		**RBPs index** (Plafkin *et al.*, 1989; Barbour *et al.*, 2002)		**QBR index** (Munné *et al*, 1998)		**River flow** (m^3/s)	**Waterfall height** (m)	**Water velocity** (m/s)	**Water physicochemical parameters** (at the water intake upstream of the fish ramp)			
		100 m down-stream	100 m up-stream	100 m down-stream	100 m up-stream	100 m down-stream	100 m up-stream	Gauging station EA013	Fish ramp	Fish ramp	Temper. (°C)	Ele. Con. (µS/cm)	pH	Dis. Ox. (mg/l)
May 2013	Mean	**93**	**93**	**176**	**17**	**90**	**10**	**1.290**	**0**	0.3	**12.8**	**520**	**8.4**	**11.8**
	Max.	-	-	-	-	-	-	2.524	0	1.1	16.5	630	8.6	19.9
	Min.	-	-	-	-	-	-	0.664	0	0.1	8.2	274	7.5	8.03
October 2013	Mean	**93**	**93**	**176**	**17**	**90**	**10**	**0.161**	**0.11**	0.8	**14.6**	**568**	**7.9**	**8.98**
	Max.	-	-	-	-	-	-	0.523	0.12	1.4	16.3	649	8.3	12.4
	Min.	-	-	-	-	-	-	0.126	0.09	0.1	11.6	492	7.5	7.00

Fish ramp

Its weir was 0.3-0.4 m high during the study period. There was an appropriate entrance location (from downstream to upstream), as close as possible to the weir, and a pool with enough depth (0.37-0.57 m).

This gauging station (with its fish ramp) was included in the very good quality of river connectivity for fish (score of 95) following the ICF index (Solà *et al.*, 2011), considering native intra-river migratory species (potamodromous) with moderate capacity to overcome obstacles (G3a group, large cyprinid species or similar), large migratory species (catadromous; G2 group, eel), and intra-river migratory species (potamodromous) with high capacity to overcome obstacles (G4 group, trout).

At times in spring (30% of days, 8 days out of 27) and often in autumn (75 % of days, 21 days out of 28), at one or more sections of this fish ramp, water velocity was excessive (> 0.6 m/s) for small species with little capacity to overcome obstacles (ICF's G3b group), like Pyrenean minnow (*P. bigerri*). If this was considered a native species, this gauging station would achieve only a moderate range of river connectivity quality (score of 75) following the ICF index (Table 14). In addition, in autumn (dry and warm) a small waterfall appeared at the entry downstream of the fish ramp (average of 0.11 m and max. of 0.12 m), but it never exceeded the maximum acceptable value (0.20 m) for this fish group (G3b).

Table 14 (next page). Hydrological data (velocity, operating levels of the fish pass and water depths and waterfall heights) of 7 sections of the fish ramp at the gauging station (EA013) on the Fluvià river at Olot (NE Catalonia), measured daily during the two study periods of 2013 (May and October). Colours indicating ICF index (Solà et al., 2011) limits are also shown. Legend: blue: follows the recommended limits for all fish groups; green: exceeds the recommended limits for small cyprinids (G3b group); yellow: exceeds the recommended limits for anguilids (G2 group); orange: exceeds the recommended limits for big cyprinids (G3a group); red: exceeds the recommended limits for salmonids (G4 group).

Prof 1 [cm]	Vel 1m [m/s]	Vel 1d [m/s]	Vel 1c [m/s]	Cabal [L/s]	Prof 2 [cm]	Vel 2m [m/s]	Vel 2d [m/s]	Vel 2c [m/s]	Prof 3 [cm]	Vel 3m [m/s]	Vel 3d [m/s]	Vel 3c [m/s]	Prof 4 [cm]	Vel 4m [m/s]	Vel 4d [m/s]	Vel 4c [m/s]	Prof 5 [cm]	Vel 5m [m/s]	Vel 5d [m/s]	Vel 5c [m/s]	Prof 6 [cm]	Vel 6m [m/s]	Vel 6d [m/s]	Vel 6c [m/s]	Prof 7 [cm]	Vel 7m [m/s]	Vel 7d [m/s]	Vel 7c [m/s]
54	0.7	0.4			51	1,1	1,0		50	1,4	1,2		44	1,6	1,3		43	1,9	2,1		46	2,1	2,0					
117	0.6	0.3	0.3		56	0,6	0,2	0,5	56	1,0	0,7	0,4	55	1,2	0,8	1,1	43	1,6	0,2	0,3	43	2,0	0,7	0,4				
105	0.4	0.3	0.5		60	0,7	0,6	0,3	40	1,3	1,0	0,2	35	1,7	0,4	0,3	33	1,2	1,2	0,2	52	1,8	1,8	0,3				
75	0.3	0.3	0.3		43	0,6	0,5	0,4	32	1,3	0,8	0,7	29	1,6	1,0	0,2	25	0,5	0,9	0,1	21	1,6	0,6	0,3				
70	0.2	0,0	0.3		40	0,4	0,3	0,3	29	1,0	0,7	0,4	20	1,4	1,0	0,3	24	0,7	0,7	0,1	24	1,7	1,0	0,3				
70	0.2	0.1	0.1		46	0,4	0,3	0,3	26	1,0	0,6	0,2	27	1,4	1,1	0,4	22	0,8	0,5	0,1	25	1,6	0,9	0,3				
60	0.2	0.05	0.3		43	0,4	0,3	0,3	25	1,1	0,6	0,6	26	1,3	1,0	0,4	23	0,8	0,7	0,1	26	1,4	0,4	0,2				
60	0.2	0.05	0.1		45	0,4	0,3	0,3	20	1,0	0,7	0,1	26	1,4	1,1	0,4	21	1,1	0,7	0,2	24	1,5	1,2	0,2				
60	0.2	0.1	0.2		45	0,4	0,2	0,3	27	1,0	0,7	0,2	26	1,3	1,0	0,4	20	0,9	0,6	0,1	25	1,2	1,1	0,2				
60	0.2	0.05	0.1		45	0,3	0,1	0,1	26	1,0	0,4	0,7	25	1,2	1,1	0,3	21	0,9	0,4	0,1	20	1,2	1,0	0,2				
66	0.1	0.05	0.1		43	0,2	0,1	0,1	25	0,9	0,3	0,2	24	1,0	0,3	0,2	13	0,5	0,2	0,1	23	1,2	0,7	0,1				
83	0.6	0.2	0.4		67	0,7	0,6	0,4	44	1,3	1,0	0,3	41	1,5	1,4	0,5	45	1,5	0,7	0,2	33	2,0	1,9	0,2				
92	0.6	0.2	0.1		62	0,7	0,6	0,4	50	1,0	0,9	0,7	47	1,3	1,2	0,5	45	1,4	1,5	0,5	41	2,1	1,4	0,9				
76.5	0.4	0.3	0.2		54	0,6	0,6	0,4	55	1,3	0,9	0,1	52	1,3	1,4	0,4	20	0,7	0,6	0,1	20	1,6	0,9	0,1				
74.5	0.3	0.05	0.2		50	0,5	0,4	0,3	51	1,1	0,8	0,1	50	1,4	1,3	0,4	24	0,6	0,5	0,1	50	1,6	1,2	0,2				
70.5	0.2	0.05	0.3		40	0,5	0,3	0,3	29	1,1	0,8	0,1	20	1,4	1,2	0,4	23	0,8	0,6	0,1	27	1,4	1,3	0,2				
70	0.3	0.2	0.2		47	0,5	0,4	0,3	29	1,0	0,7	0,1	27	1,4	1,1	0,4	24	0,6	0,6	0,1	27	1,4	0,9	0,2				
						0,5	0,4	0,3		1,1	0,8	0,3		1,4	1,0	0,4		1,0	0,7	0,1		1,6	1,1	0,3				
65	0.2	0.05	0.1		50	0,2	0,1	0,1	23	0,6	0,5	0,9	24	1,1	0,8	0,6	20	1,0	0,1	1,0	18	1,1	1,2	0,3				
60	0.1	0.05	0.05		27	0,2	0,1	0,1	20	0,7	0,5	0,8	20	1,1	0,8	0,2	16	0,7	0,1	0,5	16	0,6	0,6	0,7				
59	0.1	<0.05	<0.05		26	0,2	0,1	0,1	19	0,6	0,4	0,8	17	1,0	0,1	-	15	0,9	0,2	0,3	15	1,3	0,9	0,6	7			
58	0.1	0.05	0.05		53	0,1	0,1	0,1	18	0,4	0,3	0,7	17	0,9	0,2	0,1	13	0,8	0,2	0,1	17	0,8	0,5	0,1				
58	0.1	<0.05	<0.05		51	0,1	0,1	0,1	18	0,4	0,1	0,7	18	0,9	0,3	0,1	12	0,7	0,3	0,1	18	0,9	0,4	0,1				
58	0.1	<0.05	<0.05		57	0,1	0,1	0,1	19	0,4	0,2	0,7	17	0,8	0,4	0,1	14	0,8	0,2	0,1	19	0,9	0,6	0,2				
56.5	0.1	<0.05	<0.05		52	0,1	0,1	0,1	18	0,2	0,1	0,6	16	0,7	0,3	0,1	13	0,6	0,2	0,1	18	0,7	0,4	0,1				
57	0.1	0.05	0.05		52	0,1	0,1	0,1	17	0,1	0,2	0,6	16	0,7	0,3	0,4	12	0,6	0,2	0,1	17	0,6	0,7	0,1	4	1,5	0,4	1,1
57.5	0.1	0.05	0.05		52	0,1	0,1	0,1	18	0,1	0,2	0,7	17	0,2	0,4	0,7	14	0,4	0,2	0,1	18	0,7	0,2	0,1	4	1,6	0,5	1,3
58	0.1	<0.05	<0.05		53	0,1	0,1	0,1	18.5	0,6	0,2	0,7	18	0,6	0,3	0,8	14	0,7	0,2	0,1	19	0,6	0,7	0,1	3	1,6	0,7	1,3
57	0.1	<0.05	<0.05		52	0,1	0,1	0,1	17	0,2	0,1	0,6	15	0,5	0,2	0,7	13	0,5	0,2	0,2	17	0,6	0,1	0,1	3	1,5	0,7	1,7
56.5	0.1	<0.05	<0.05		55	0,1	0,1	0,1	17	0,2	0,1	0,6	15	0,3	0,2	0,8	13	0,7	0,3	0,1	17	0,6	1,0	0,1	3	1,5	0,7	1,1
56.7	0.1	<0.05	<0.05		52.5	0,1	0,1	0,1	16	0,3	0,2	0,6	17	0,8	0,3	0,8	13	0,5	0,3	0,1	18	0,8	0,8	0,1	3	1,5	0,8	1,2
56.5	0.1	<0.05	<0.05		52.5	0,1	0,1	0,1	17	0,2	0,1	0,6	17	0,6	0,2	0,5	12	0,5	0,2	0,1	16	0,6	0,8	0,1	3	1,6	0,7	1,6
56.5	0.1	<0.05	<0.05		53.5	0,1	0,1	0,1	16.5	0,2	0,1	0,8	16	1,0	0,3	1,4	12	0,6	0,2	0,1	17	0,6	1,5	0,1	4	1,5	0,8	1,3
56.5	0.1	<0.05	<0.05		51.5	0,1	0,1	0,1	17	0,9	0,1	1,3	16	1,0	0,3	1,4	12	0,6	0,2	0,1	17	0,6	1,5	0,1	4	1,5	0,8	1,3
56	0.05	<0.05	<0.05		54	0,1	0,1	0,1	17	0,6	0,1	1,1	17	0,2	0,1	0,6	12	0,5	0,1	0,1	17	0,4	1,5	0,1	4	2,8	1,4	1,2
56	0.05	<0.05	<0.05		54	0,1	<0,05	<0,05	16.5	0,5	0,3	0,8	15	0,9	0,1	0,4	12	1,1	0,4	1,6	16	0,7	1,0	1,1	4	3,0	1,4	2,0
57	0.05	<0.05	<0.05		54	0,1	0,1	0,1	18	0,2	0,3	1,3	18	0,9	0,3	0,1	12	1,1	0,4	1,6	18	0,8	0,8	0,1	6			
57	0.1	0.05	0.05		54.5	0,2	0,1	0,1	17	0,4	0,3	0,7	17	1,1	0,3	0,6	13	1,1	0,2	0,2	18	1,0	1,1	0,1	4	1,6	0,8	1,1
						0,1	0,1	0,1		0,4	0,2	0,8		0,8	0,3	0,5		0,7	0,2	0,3		0,7	0,8	0,2		1,8	0,8	1,4

(red)	> 2.4m/s	Supera el límit recomanat per a G4: salmònids
(orange)	2.1-2.4m/s	Supera el límit recomanat per a G3a: ciprínids grans
(yellow)	1.8-2.0m/s	Supera el límit recomanat per a G2: anguílids
(green)	0.6-1.7m/s	Supera el límit recomanat per a G3b: ciprínids petits
(blue)	<0.6	

Font: ICF (Solà *et al.*, 2011)

Migrating fish and fish ramp effectiveness

472 fish of 3 species were caught at the water intake upstream of the fish ramp during the whole study period (55 days): 70.5% of individuals in spring and 29.5% in autumn (Fig. 83). Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) were found on all occasions, and common carp (*C. carpio*) only in spring (Table 15).

Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) exhibited a maximum crossing rate (Fig. 83) in spring (average of 7.9 ind./day and 3.8 ind./day, respectively), and lower in autumn, slightly less for Western Mediterranean barbel (*B. meridionalis*) (4.6 ind./day) and much less for Catalan chub (*S. laietanus*) (1.0 ind./day). Maximum fish passage occurred during the spawning period (around May), a few days immediately after a high flow (9.8 m^3/s), probably as in response to a rise in water temperature (until 14.6 ºC) and at New Moon: 18.0 ind./day of Western Mediterranean barbel (*B. meridionalis*) and 25.7 ind./day of Catalan chub (*S. laietanus*). A secondary peak of passage was recorded in May two days after a moderate peak flow (2.52 m^3/s), with water temperature rising (from 10.2 to 13.4°C) and during the First Quarter. Also outside of the spawning period, in October, maximums of fish crossing rates (22.3 ind./day of Western Mediterranean barbel (*B. meridionalis*) and 6.0 ind./day of Catalan chub (*S. laietanus*)) were observed a few days after a moderate peak flow (0.52 m^3/s), with water temperature rising (until 16.0°C) and at New Moon.

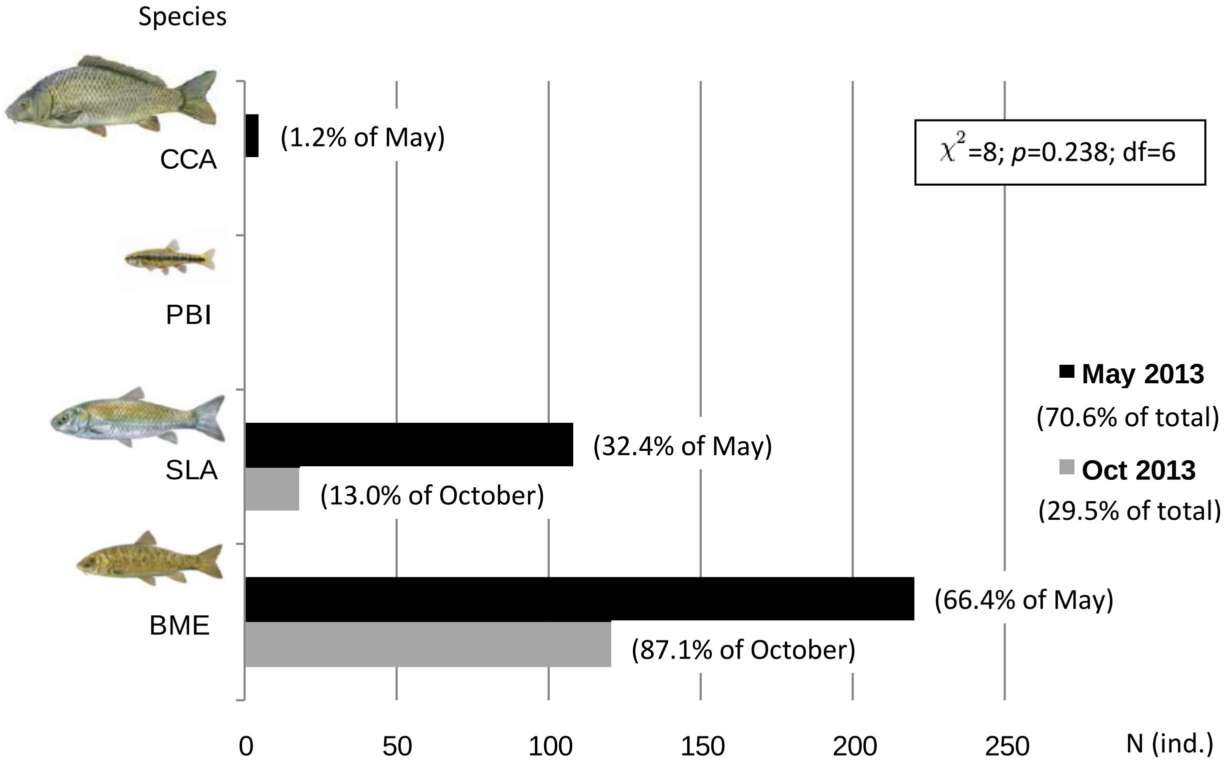


Figure 83. Species composition in number of individuals caught (and percentage) obtained by trapping at the water intake upstream of the fish ramp at the gauging station EA013 on the Fluvià river at Olot (NE Catalonia), in May (27 days) and October 2013 (28 days). Chi-square test results (comparing catches between months) are also shown. Legend: BME: Western Mediterranean barbel (*Barbus meridionalis*), SLA: Catalan chub (*Squalius laietanus*), PBI: Pyrenean minnow (*Phoxinus bigerri*), and CCA: common carp (*Cyprinus carpio*).

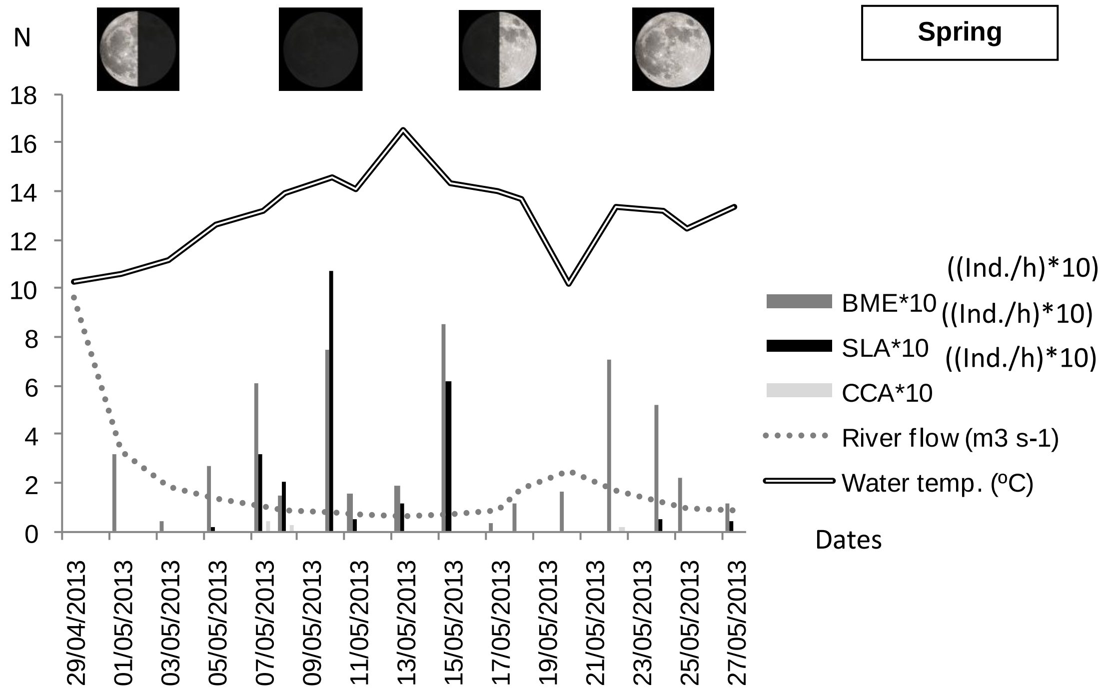
Common carp (*C. carpio*) was only detected crossing in spring (average of 0.2 ind./day, maximum of 1.2 ind./day). Pyrenean minnow (*P. bigerri*), although abundant downstream, was never observed migrating (or spawning).

Fish movements were intense when water temperature rose above 10°C for Western Mediterranean barbel (*B. meridionalis*), *and* when water temperature rose above 13°C for Catalan chub (*S. laietanus*) and common carp (*C. carpio*).

Table 15. Size of species trapped at the water intake upstream of the fish ramp on the Fluvià river at Olot (NE Catalonia), in two study periods of 2013. Legend: BME: Western Mediterranean barbel (*B. meridionalis*), SLA: Catalan chub (*S. laietanus*), and CCA: common carp (*C. carpio*).

Species	**BME**	**SLA**	**CCA**
Mean fork length (m)			
May	0.122	0.126	0.512
October	0.118	0.132	
Mean	**0.121**	**0.127**	
Range (m)			
May	0.048-0.173	0.048-0.234	0.435-0.604
October	0.069-0.198	0.050-0.232	
Mean	**0.048-0.198**	**0.048-0.234**	

Grouping fish pass rates per moon phases (Fig. 84), Western Mediterranean barbel (*B. meridionalis*) migrated with similar intensity throughout May (average range: 0.29-0.38 ind./h), coinciding with increasing water temperature (average rate from 10.6°C to 14.5°C) and decreasing water flow (average rate from 4.61 m^3/s to 0.81) after a peak flow (9.67 m^3/s). In October, Western Mediterranean barbel (*B. meridionalis*) crossing rate progressively decreased from Third Quarter (0.38 ind./h) to Full Moon (0.11 ind./h), with regular water temperatures.



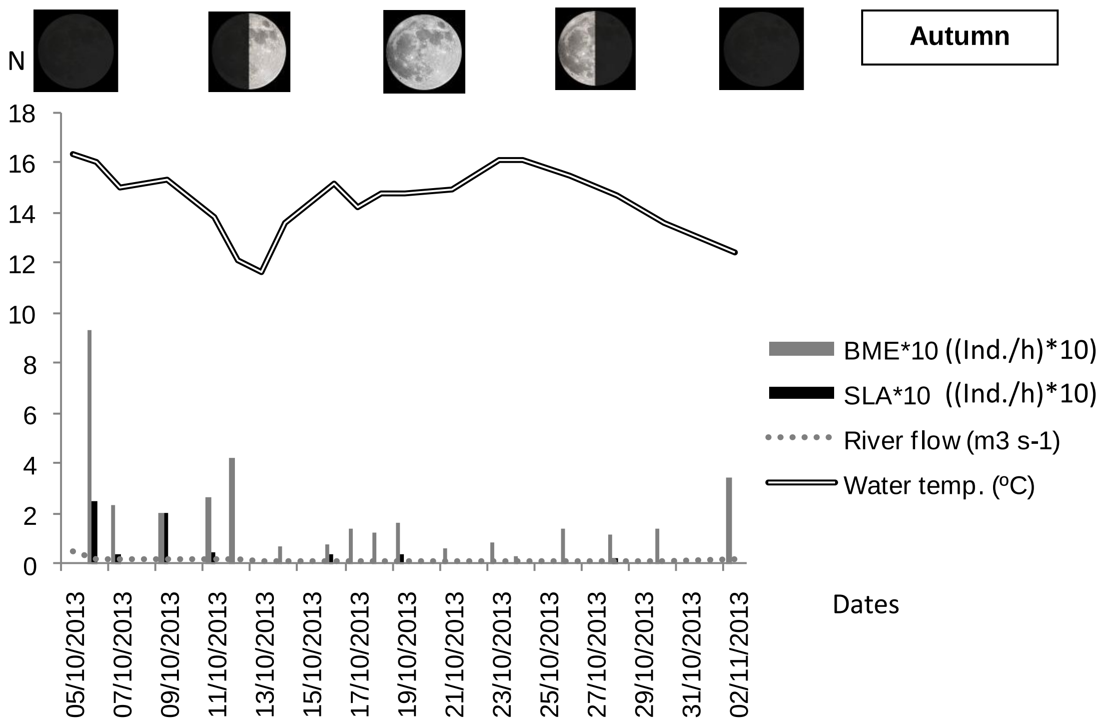


Figure 84. Fish crossing rates (ind./h*10) through the fish ramp on the Fluvià river at Olot (NE Catalonia) in spring (spawning period; top) and autumn (bottom) 2013. Daily average river flows and water temperatures, and moon phases are also shown. Legend: BME: Western Mediterranean barbel (*B. meridionalis*), SLA: Catalan chub (*S. laietanus*), and CCA: common carp (*C. carpio*).

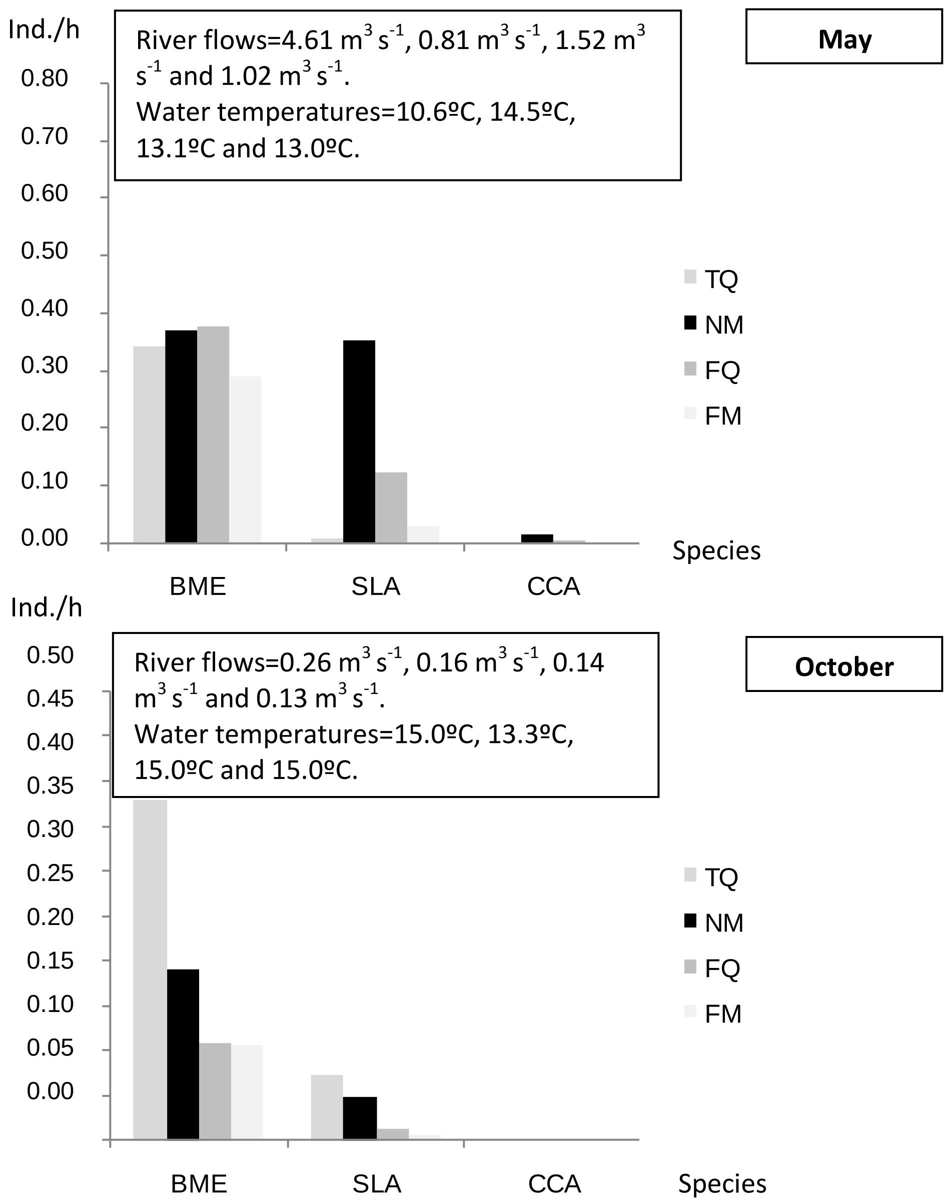


Figure 85. Fish crossing rates (ind./h) through the fish ramp on the Fluvià river at Olot (NE Catalonia), grouped per moon phases in May (spawning period; top) and October (bottom) 2013. Average river flow and water temperature for each moon phase (from third quarter (left) to full moon (right)) are also shown. Legend: BME: Western Mediterranean barbel (*B. meridionalis*), SLA: Catalan chub (*S. laietanus*), and CCA: common carp (*C. carpio*); TQ: Third Quarter, NM: New Moon, FQ: First Quarter, and FM: Full Moon.

Catalan chub (*S. laietanus*) (Fig. 85) migrated with different intensity between moon phases throughout May, especially intense during New Moon and First Quarter phases (0.35 ind./h and 0.12 ind./h, respectively), coinciding with an increase in water temperature and a decrease in water flow, greatly reduced at Full Moon and Third Quarter (average rates of 0.03 ind./h and 0.01 ind./h, respectively). In October, it was lower and also progressively decreased from Third Quarter (0.07 ind./h) to Full Moon (0.01 in ind./h). Data on common carp (*C. carpio*) crossing were scarce.

Indirect estimation

In October, fish populations on both sides of the gauging station on the Fluvià river (100 m upstream and 100 m downstream) were similar at New Moon (χ^2= 8; *p* = 0.238; df = 6). The number of catches was low at Full Moon, so the differences between both sides were uncertain (χ^2= 5; *p* = 0.287; df = 4). Otherwise, statistically significant differences in numbers between Full Moon and New Moon catches were observed (Fig. 86). At Full Moon and New Moon, river flow (0.18 m^3/s and 0.14 m^3/s, respectively) and water temperature (15.0°C and 14.8°C, respectively) were almost equal.

Direct estimation

Many individuals of Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) and some common carp (*C. carpio*) were caught at the water intake upstream the fish ramp (Fig. 83). However, both native cyprinids showed statistically significant differences in fork length between individuals downstream and migrating upstream (using the fish ramp) in spring (Fig. 87 and 88), with larger individuals negotiating the fish ramp, relatively to the ones present downstream. Despite the modest number of catches in autumn, young-of-the-year Western Mediterranean barbel (*B. meridionalis*) (fork length: FL<0.07 m; Fig. 6) and Catalan chub (*S. laietanus*) (FL<0.08 m; Fig. 88) seem to have difficulties in migrating upstream using the fish ramp during these two periods.

Average somatic condition of Western Mediterranean barbel (*B. meridionalis*) migrating upstream using the fish ramp was 3.83 mm/g in spring and 3.11 mm/g in autumn. Catalan chub (*S. laietanus*) was 4.45 mm/g in spring and 2.53 mm/g in autumn. Common carp (*C. carpio*) was 0.21 mm/g in spring. None were caught in autumn.

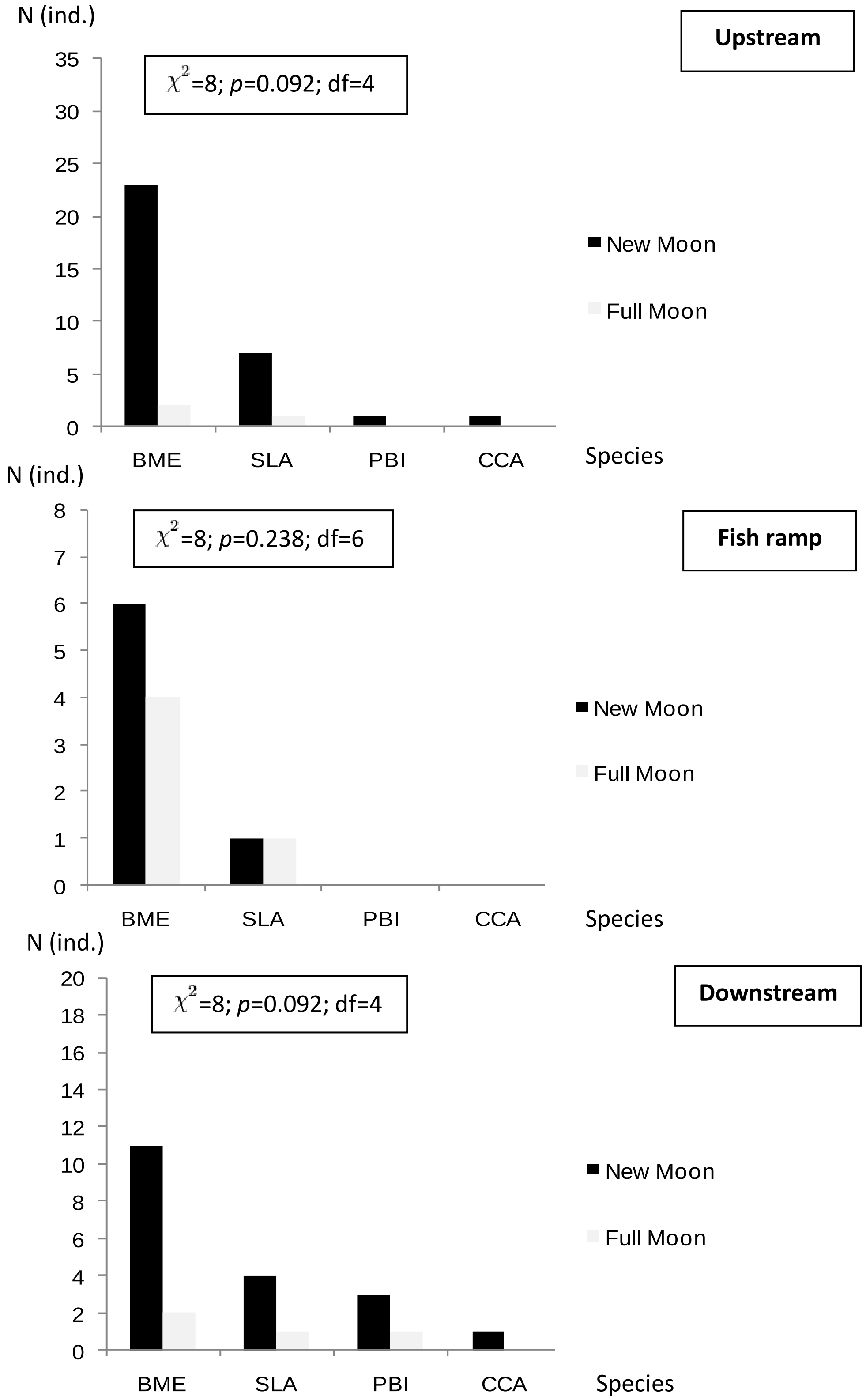


Figure 86. Species composition (in total numbers) obtained by fikenets 100 m upstream of the gauging station on the Fluvià river at Olot (NE Catalonia) (top), in the water intake upstream of the fish ramp of the gauging station (middle) and 100 m downstream of the gauging station (bottom), at New Moon and Full Moon, on 7 and 19 October 2013, respectively. Chi-square test results (comparing catches between new moon and full moon at each place) are also shown. Legend: BME: Western Mediterranean barbel (*B. meridionalis*), SLA: Catalan chub (*S. laietanus*), PBI: Pyrenean minnow (*P. bigerri*), and CCA: common carp (*C. carpio*).

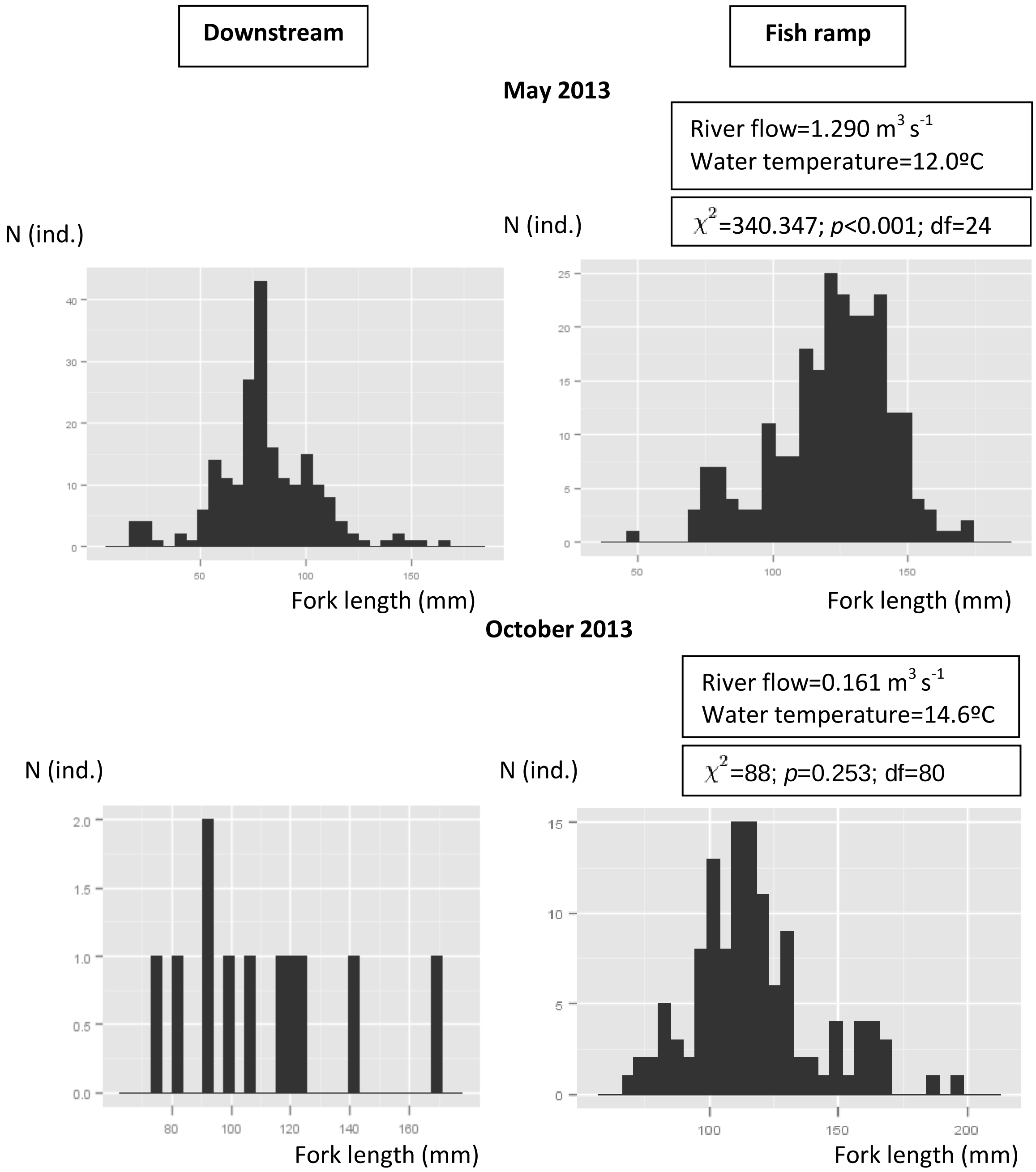


Figure 87. Western Mediterranean barbel (*B. meridionalis*) size class frequencies (fork length, mm) downstream (left) and in the water intake upstream of the fish ramp on the Fluvià river at Olot (NE Catalonia) (right) in May 2013 (top) and October 2013 (bottom). Average river flow and water temperature for each month, and Chi-square test results (comparing size class frequencies between downstream and in the water intake upstream of the fish ramp) are also shown.

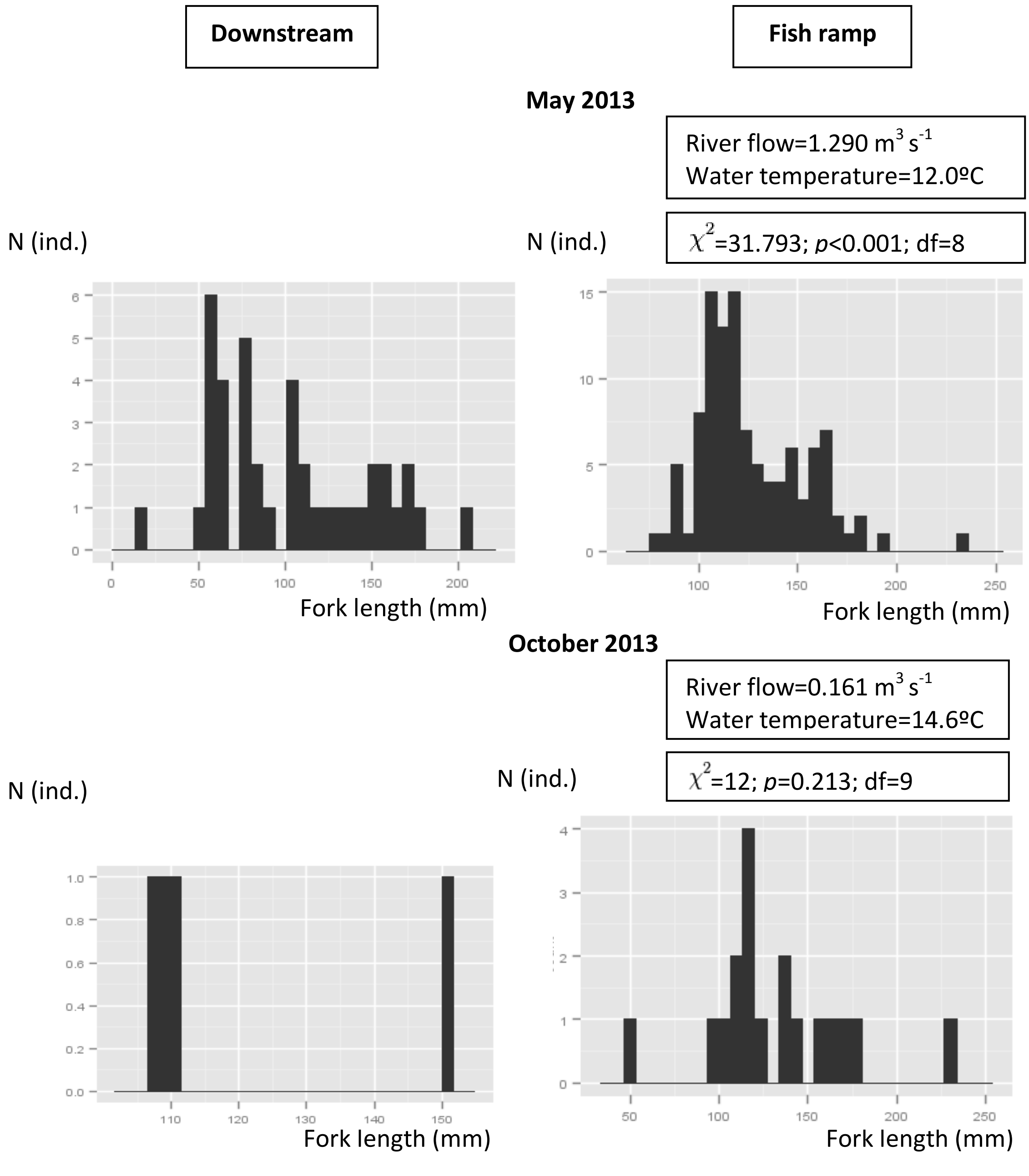


Figure 88. Catalan chub (*S. laietanus*) size class frequencies (fork length, mm) downstream (left) and in the water intake upstream of the fish ramp on the Fluvià river at Olot (NE Catalonia) (right) in May 2013 (top) and October 2013 bottom). Average river flow and water temperature for each month, and Chi-square test results (comparing size class frequencies between downstream and in the water intake upstream of the fish ramp) are also shown.

7.4. Discussion

Fish community

The Fluvià river includes a low number of freshwater fish species, like other Mediterranean small and medium river basins (Bruslé & Quignard, 2001). Brown trout (*S. trutta*), Western Mediterranean barbel (*B. meridionalis*), Catalan chub (*S. laietanus*) and European eel (*A. anguilla*) were cited in the Garrotxa region in the past (Nadal-Fortià, 1964). A first recent survey (Moreno-Amich *et al*., 1996) detected these 4 native fish species. In 2008, a sampling showed that Western Mediterranean barbel (*B. meridionalis*) was present everywhere and was the most important fish species (Clavero *et al*., 2008), Catalan chub (*S. laietanus*) was also present but not abundant and European eel (*A. anguilla*) and brown trout (*S. trutta*) were still present. Common carp (*C. carpio*) was the only one exotic fish living there.

European eel (*A. anguilla*) was not found on the present study. The absence of this tolerant species of wide distribution throughout the sampling campaigns and its shortage in previous samplings (Clavero *et al*., 2008), mainly associated with regular repopulation, indicate that the Fluvià is still too fragmented and poorly connected with the Mediterranean Sea. Its recovery would require complementary actions at entire watershed scale, improving river connectivity from sea to source.

Brown trout (*S. trutta*) was also not found. Released during decades in big numbers from fish farms, now it is prohibited. Global warming could also have had a seriously effect: the increase in water temperature recorded over recent decades in Iberian rivers appears to be associated with a brown trout decline (Almodóvar *et al.,* 2012).

Observed fish densities and biomass (over 1500 individuals and 100 kg per ha, respectively) are considered symptomatic of a good population in Iberian rivers (Sostoa *et al.*, 2010). However, diagrams of size class frequencies of Western Mediterranean barbel (*B. meridionalis*) (see Figure 6) reflect a certain dominance of the age group young-of-the-year, with an average length remaining below 0.100 m. This may be associated with fluctuating populations subject to frequent disturbances (Clavero *et al*., 2008).

The fact that the size class of fish found downstream of the gauging station is slightly different to fish able to overcome this fish ramp during the spawning period (Fig. 87 and 88) does not necessarily indicate a malfunction of this fish pass; it could be related to reproductive individuals which remain in lower areas because they have suitable habitat downstream to fulfill their reproductive/feeding needs.

The decrease in fish somatic condition between spring and early autumn is probably associated with the great food availability in spring and summer, in a watercourse with a high oxygen availability and riparian vegetation (Vila-Gisbert *et al*., 2000), coinciding with other studies in this locality (Clavero *et al*., 2008) and other rivers in NE Catalonia (Ordeix *et al*., 2011). The average somatic condition was also lower for fish crossing the fish ramp, probably the healthiest fish population.

Although here is a weakness for the temporarily limited data (which does not cover all pre / reproductive, either, every month of the year), the spawning period of Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) (at least between 10th May and 15th July 2013) coincides well with previous information (Sostoa et al., 1990; author's unpublished data); it also could be initiated before, in March (Zamora *et al*., 2011). The common carp (*C. carpio*) spawning period occurs between April and July (Sostoa *et al*., 1990; author's unpublished data) and the Pyrenean minnow (*P. bigerri*) spawning period happens between April and July (Doadrio, 2001; Leunda *et al*., 2010; author's unpublished data). Therefore, these species were detected mainly crossing the fish ramp during this period, except Pyrenean minnow (*P. bigerri*), although it is abundant downstream. This could be related to the fact that the sampling period did not coincide with the Pyrenean minnow (*P. bigerri*) spawning period in 2013, probably delayed by low water temperatures in May.

Fish ramp

The fish ramp of the gauging station on the Fluvià River at Olot is very effective for all native fish species. Results of the quick assessment procedures following the ICF index agree with the observed fish pass effectiveness for large cyprinid species, intra-river migratory species (potamodromous) with a moderate capacity to overcome obstacles

(*B. meridionalis* and *S. laietanus*), using indirect and direct techniques. European eel (*A. anguilla*) could also theoretically use the fish ramp, and is able to pass along the river bank as well.

Although an invasive species, big individuals of common carp (*C. carpio*) were also observed migrating through this fish ramp, coinciding with a previous fish ramp assessment in Catalonia (minimum FL of 0.436 cm (n=18), in the Ter river at Manlleu, NE Catalonia, with an ICF index of 85, in May 2012; author's unpublished data).

Pyrenean minnows (*P. bigerri*), an intra-river migratory species with a low capacity to overcome obstacles, a non-native at this basin, was never observed crossing. Water velocity into the fish ramp could be too high (> 0.6 m/s) related to the small size of fish (and hence lower swimming performance).

Although larger individuals prevail slightly against younger crossing the fish ramp (see figures 87 and 88), populations from the two sides of the gauging station are almost equivalent and a barrier effect (following Solà *et al*., 2011) is not clearly observed.

When waterfalls do not exceed 0.10 m in height and/or water velocity is lower than 0.5 m/s, most species and individuals are able to cross a fish pass, including small species with low capacity to overcome obstacles, such as Pyrenean minnows (*P. bigerri*), European eel (*A. anguilla*) and young-of-the-year of brown trout (*S. trutta*) and Western Mediterranean barbel (*B. meridionalis*), according to previous data of several fish passes in Catalonia (Ordeix *et al*., 2011). However, water velocities of 1.0-1.2 m/s at the downstream entrance are also accepted by smaller Iberian cyprinids (Santos *et al*., 2004). Therefore, we cannot ignore the possibility that the small waterfall (> 0.10 m) that appeared at the entry downstream of the fish ramp during very low flows, and especially several water velocities inside the fish ramp (> 0.5 m/s), could temporally affect part of the surrounding fish population, at least their home range.

Fish migration

Observed crossing rates of Western Mediterranean barbel (*B. meridionalis*) in the fish ramp in May (average of 7.9 ind./day) and October (average of 4.6 ind./day) are significant (the maximum known in Catalonia to date). Despite the own year variability of Mediterranean species, previous studies in similar river size and the same species showed a slightly lower average. In the Llémena stream, in the Ter river basin, the range was 1.3-3.0 ind./day in spring and 0.2 ind./day in autumn (Ordeix *et al*., 2011), where many individuals (mostly males, with a smaller size than females) had difficulties to cross. Although that depends on the population size of migratory fish and, at the same time, on the size of the river, higher values were obtained for other cyprinids especially in spring, as is the case of Iberian barbel (*Luciobarbus bocagei*) in a tributary of the Duero river at north of Spain, with a range of 0.5-14.0 ind./day (Sanz et al., 2013).

Significant movements of fish were mostly associated with their particular spawning periods and following high or moderate peak flows, as indicate many studies (Reiser & Peacock, 1985; Lucas & Baras, 2001; Marmulla & Welcomme, 2002). Fish passage rates of freshwater Iberian cyprinids are very high in spring (April-June), with a peak passage in May, associated with their spawning period, but not only then (Santos *et al*., 2012; author's unpublished data). Water temperature seems to be an important factor driving cyprinids upstream, highlighting it as an important cue controlling the intensity of fish migration (Rodriguez-Ruiz & Granado-Lorencio, 1992). Crossing rates of Iberian cyprinids increase significantly when water temperature rises above 13°C (Santos *et al*., 2012; Sanz *et al*., 2013; author's unpublished data from the Ter river).

In relation to the lunar cycle, large differences in fish activity between New Moon and Full Moon were observed for all species, both in upstream and downstream river stretches, and also through the fish ramp. In May, coinciding with the spawning period, Western Mediterranean barbel (*B. meridionalis*) was very active throughout the lunar cycle. In October, it mostly moves in the Third Quarter and at New Moon. Although reproduction of Western Mediterranean barbel (*B. meridionalis*) could be during the day and at night, a largely nocturnal behaviour outside the spawning season has been described (Poncin, 1994). Fish activity during less bright moon phases coincides with the fact that Iberian cyprinids, Fish activity during less bright moon phases coincides with the fact that Iberian cyprinids, i.e. Iberian barbel (*L. bocagei*), Iberian nase (*P. polylepis*) and Iberian chub (*Squalius carolitertii*), among others, i.e. brown trout (*Salmo trutta*) and sea lamprey (*Petromizon marinus*), show significant nocturnal preferences in their upstream movements (Santos *et al*., 2004; Sanz *et al*., 2013). Migrations mainly occur at night and twilight periods, when survival chances from visual predators are presumably higher (Prignon *et al*., 1998).

7.5. Conclusions

We highlight that the physical conditions of the fish ramp at the gauging station on the Fluvià river at Olot (NE Catalonia), included in the very good quality of river connectivity for fish (score of 95) following the ICF index (Solà *et al*., 2011), allow the passage of the native cyprinid species in this river, at least, in spring and autumn. Big individuals of common carp (*C. carpio*), an invasive species, were also observed migrating through this fish ramp in spring. Pyrenean minnows (*P. bigerri*), the other non-native at this river basin, was never observed crossing.

Otherwise, young-of-the-year Western Mediterranean barbel (*B. meridionalis*) and Catalan chub (*S. laietanus*) seem to have difficulties in migrating upstream using the fish ramp. We cannot ignore the possibility that the small waterfall (> 0.10 m) that appeared at the entry downstream of the fish ramp during very low flows, and especially several water velocities inside the fish ramp (> 0.6 m/s), related to the small size of fish (and hence lower swimming performance), could temporally affect part of the surrounding fish population.

Despite the own year variability of Mediterranean species, fish crossing rates in the Fluvià river at Olot are significant and very high in spring (May), associated with the spawning period of native freshwater cyprinids, coinciding with other Mediterranean inland waters. In addition, fish crossing rates of native cyprinids are lower but also important in autumn (October).

Pending of complementary samplings all around several years, the spawning period seems to be the primary driver of upstream fish migration for these cyprinids, but a decrease in river flow following a peak flow, a minimum value of water temperature (above 10°C for Western Mediterranean barbel (*B. meridionalis*) and 13°C for Catalan chub (*S. laietanus*) and common carp (*C. carpio*)) and less bright lunar phases seem to be also important.

8. Final conclusions

These studies have shown that:

(1) Almost all Iberian freshwater fish clearly migrate. The great majority are potamodromous species but there are also diadromous species (in an equal proportion of anadromous and catadromous).

(2) Fish migrating rates for most Iberian and Mediterranean freshwater fish, both potamodromous (cyprinids, etc.) and diadromous (sturgeons, shads, mullets, etc.), are very high in spring, associated with the prevailing spawning period in the area but also for feeding and refuge. Other groups (salmonids, eel, etc.) migrate especially between autumn and spring.

(3) Spawning, dispersion, feeding, refuge and displacement are associated with migration behaviour.

(4) For most Mediterranean freshwater fish, the reproductive and other migrating periods are particularly long and variable from year to years, adapting these periods to the great year-on-year variability (i.e. of rainfall and water temperature) that is characteristic of the Mediterranean climate. Most females have multiple spawning (they can spawn several times each year), being an advantage in the highly unpredictable hydrological regime of Mediterranean environments. At lower latitudes, spawning and other migrating periods are earlier, and later for autumn and winter spawners and migrators.

(5) The principal cues or factors which influence fish migration behaviour of Iberian freshwater fish migration are: sexual maturity and condition of fish, diurnal/nocturnal rhythm or photoperiod, water temperature, river flow, water currents or hydrological conditions, tidal cycle in estuaries, meteorological conditions, large oceanic features, moonlight, turbidity, salinity and water quality. The possible relationship between electric and magnetic fields and imprinted or inherited information on a route with Iberian freshwater fish migration has not yet been assessed.

(6) The spawning period seems to be a primary driver of upstream fish migration, but for most species a decrease in river flow just after a peak flow or water level changes, a minimum of water temperature and less bright lunar phases seem to be also important.

(7) Migrations take place particularly in the spawning period and throughout the year for feeding and refuge. Considering all the various species present in each river, the own year variability of Mediterranean climate and species, spawning migration and other migration movements cover all or practically all year round.

(8) Unrestricted movement is almost a permanent requirement. Thus, if Iberian and other Mediterranean rivers, lakes and coastal lagoons were not absolutely connected (without transverse obstacles), at least, all fish passes would almost always (all year round) be in operation.

(9) Ecological connectivity for fish in Catalan rivers is generally bad: fish passes are only present in 11% of obstacles and many of these (61%) do not adequately address the requirements of native fish species or are poorly maintained. Dam and weir removal and close-to-nature fish passes are very few. Maintenance and regular assessment during the design and implementation of each fish pass project is also pending.

(10) River connectivity has been little developed, without the necessary coordination to improve fish migration at entire watershed scale, as is especially necessary to recover, among others, the European eel (*A. anguilla*) from sea to source in most Catalan river basins.

(11) Fish crossing rates at apparently suitable fish passes are, with few exceptions, too low and, in most cases, only the upstream movements of fish species with a high capacity to overcome obstacles, such as salmonid, or the largest individuals, often predominantly females, succeed in migrating.

(12) Close-to-nature fish passes following international guidelines, such as the two assessed fish ramps on the Ter and Fluvià rivers, allow passage of all native cyprinid species and individuals of almost all sizes in these river basins.

(13) Although the results of implementing the ICF index and *in situ* assessments at the 10 + 1 assessed fish passes are consistent, these river connectivity index have to be applied to more fish passes to be validated. If necessary, both methodologies and different types of solutions to improve fish migration and native species conservation should be enhanced.

(14) It is necessary to improve knowledge on migratory behaviour and crossing rates all year round in different fish passes for most native Iberian and Mediterranean freshwater fish species, especially those with less socio-economic interest (but no less biological and ecological interest), and downstream migration for all species.

(15) Due to the high variability in jumping and swimming capabilities of native fish species, and the great diversity of river stretches and river types, it is essential in all cases to carefully assess each new fish pass that is implemented, at least during spawning periods of native fish species, but not only at this time.

(16) Moreover, fish pass assessment also provides insight into fish movement patterns to improve information on periods and possible associated causes of Catalan, Iberian and Mediterranean freshwater fish migration.

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And to the fish, who yet it move...

Figure 89. Thinlip grey mullet (*Liza ramada*) going upstream in the Ter river under the Torroella de Montgrí bridge (El Baix Empordà region) in spring 2006.

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